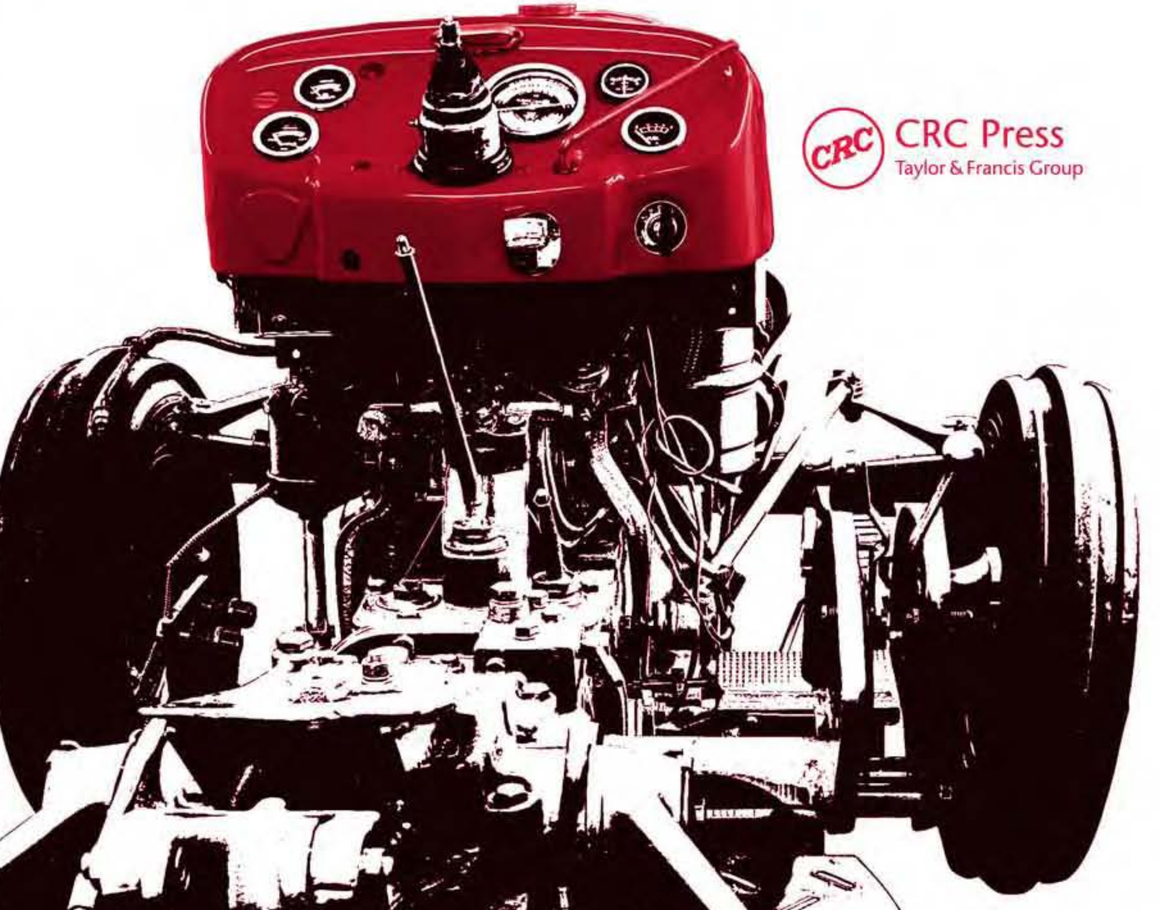
# PAINT TECHNOLOGY HANDBOOK

Rodger Talbert



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# Preface

Paint has been used for artwork for many thousands of years. The oldest Mediterranean civilizations including the Greeks, Romans, and Egyptians used encaustics, paints made with a mixture of mineral pigments (iron, copper, manganese oxides, etc.), melted beeswax, and resin and then fixed with heat. Tempera, a fluid mixture of binder (organic medium), water, and volatile additives (vegetal essential oils) and organic binders made of materials available from animal sources (whole egg, animal glues, or milk) were used to make paints for hundreds of years.

At the end of the Roman Empire and up to the Renaissance period (fifteenth century), these ancient formulas were lost and replaced by oil paint and/or tempera. In Italy and Greece, olive oil was used to prepare pigment mixtures, but the drying time was excessively long and unpredictable. Gradually, paints were refined with different oils and additives, working in combination with heat, to produce a group of reliable resin systems and solvent blends for modern industrial coatings that provide the appearance characteristics to satisfy consumers and protective characteristics to make the product last in different environments and conditions. Modern coatings are now used on virtually every durable-good product manufactured.

In more recent history, the need to clean up the environment has had a profound impact on coating formulation. Higher solids content and water content have changed to reduce the solvent included in the blend and reduce waste and emissions generated by the use of surface coatings.

Surface coatings are used on furniture, toys, automobiles, bicycles, computer cabinets, televisions, and thousands of other products. Many of these products are coated with liquid organic paints. Paint provides a decorative or protective coating on a metal, plastic, or wood product. Paint is also applied for insulation, to reflect light, or conduct electricity.

The average person can see the decorative value of paint, and many products are purchased because of eye appeal. Although it is less obvious at the time of purchase, resistance to the elements is equally important, and consumers appreciate the fact that the products they own will stay cleaner, last longer, and resist corrosion because they are protected by a high-quality industrial coating.

# Author

**Rodger Talbert** is an independent consultant working in surface finishing technology. He designs new systems for liquid spray coating, powder coating, and electrodeposition, and works to improve existing systems through process improvement, retrofit, and training.

Talbert began his career in coatings in 1976, working for a company involved in custom coating and metal fabrication. He also worked 7 years for a company that designs and builds coating systems. He started his own business, R. Talbert Consulting, Inc., in 1993.

Talbert has taught Powder Coating and Finishing System Design and Operation at Grand Rapids Community College, where he designed and implemented a Finishing Technician Certificate program and published six training manuals for liquid coating, electrocoating, and powder coating classes. He is the editor of *The Powder Coater's Manual*, and he is a member of the technical advisory committee for the Iowa Waste Reduction Center. He also conducts periodic training workshops in liquid coating spray technique, powder coating, and systems design.

Talbert received his education in business administration at Aquinas College in Grand Rapids, Michigan. He is a member of the Powder Coating Institute (PCI) and a member of the Electrocoat Association. He is the former chairman of the Application & Recovery Committee of the PCI, chairman of education for Chemical Coaters Association (CCAI), technical director for CCAI, and former president of the National Board of Directors for CCAI.

He has written and presented numerous technical papers for SME/AFP, PCI, and CCAI. He has contributed to the *SME Design for Manufacturing* handbook on the subject of powder coating, is a contributor to the *PCI Powder Coating Terms & Definitions* handbook, and is a contributor to the *PCI Powder Coating Manual* and *The Complete Finishers Handbook*. He also wrote the chapter on powder coating in the *Manufacturers Engineering Handbook*, published by McGraw-Hill.

# 1 Part Preparation Processes and Equipment

A coating is applied to a part to enhance its appearance and to protect the substrate material. An organic coating will act as a physical barrier to moisture, but if the coating surface is damaged, the bare metal is exposed, and corrosion can form and spread. The adhesion of the coating and the corrosion resistance of the product depend on the preparation of the surface. Part preparation is often referred to as pretreatment.

The term pretreatment is used to define the mechanical or chemical surface treatment for a manufactured product, referred to as the substrate, to clean it, and prepare it for the application of a coating. Pretreatment can be accomplished in many different ways. For example, sanding a part to remove dirt is a simple mechanical method of part preparation. Chemical pretreatment may be as simple as a solvent wipe, or it may be a multistage spray washer that cleans the part and applies a conversion coating. The specific method and degree of pretreatment used depends on quality requirements of the product.

Pretreatment typically provides better adhesion of the coating to the part and helps prevent the spread of corrosion, adding value to a product and extending its useful life. Pretreatment eliminates reactions between metals and between coatings and metals. It also cushions expansion and contraction differences between the substrate and the coating.

Pretreatment is one of the most important steps in ensuring that the coating will perform as intended. A decorative coating will not hide defects, and the performance of a coating is directly related to the condition of the surface that it is applied to. Application of the coating over a contaminant will prevent it from forming a tight bond to the substrate, and if the contaminant lifts off, so will the coating. Dirt particles will not dissolve or be hidden by the coating. For good appearance and adhesion, the part must be clean.

In addition to cleaning, it may be necessary to develop a conversion coating on metal surfaces prior to coating application. With the exception of some precious metals such as silver, gold, and platinum, metals react with air to form an oxide layer on their surface. Water molecules are tightly held to this oxide layer. This is not a good surface condition for chemical bonding. An example of a surface that has been treated with a conversion coating is shown in Figure 1.1.

Deciding what process can be used to pretreat a particular part depends on the performance requirements of the final part, pretreatment requirements of the paint to be used, the substrate material, and soils on the surface.

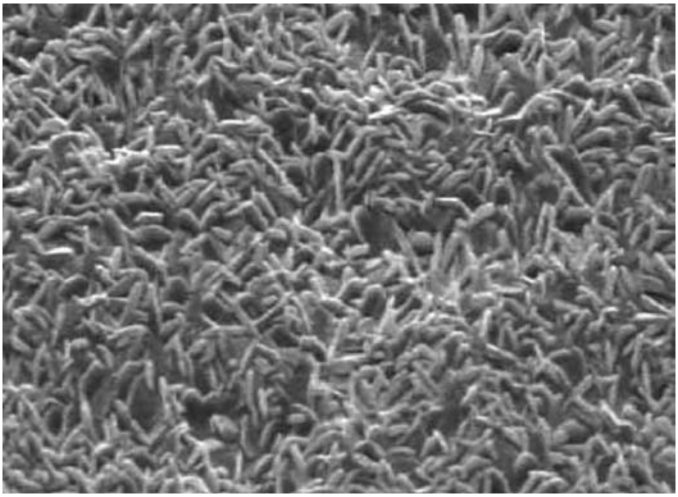


**FIGURE 1.1** Magnified zinc phosphate surface.

## 1.1 CLEANING

Manufactured products have a variety of contaminants on their surfaces. Before a coating is applied to the substrate, the surface has to have these contaminants removed. If contamination is left on the surface, the coating may not meet the required quality standards for appearance, adhesion, or corrosion resistance.

The kind of pretreatment to use will depend on the types of soil found on the surface and the quality goals for the product. A good definition of the level of performance that is required will lead to a cleaning process that is effective and reasonable in cost.

### 1.1.1 Types of Soil

Raw materials that are stored, handled, or used for manufacturing products will always have some surface contamination. On metals, the probable contaminants are oily soils, including petroleum products, animal fat, or vegetable oils deposited during manufacturing operations for rust protection, drawing, machining, and forming. There may also be heavy-duty drawing compounds and lubrication greases or waxes and some solid soils such as carbon, graphite smuts, metal shavings, polishing products, metal oxides, welding scale, and rust or corrosion.

Plastics may have mold release, skin oils from handling, plastic particles from sanding, and dust and dirt from the atmosphere.

There are a variety of mechanical and chemical methods that can be used to clean metals and plastics. Accurate identification of soils leads to the proper cleaner selection and helps verify cleanliness. The first step is to do a soil audit to determine what types of soils will need to be removed.

#### 1.1.1.1 Rust Inhibitors

Lubricants, paraffin waxes, oils, drawing compounds, and similar rust inhibitors are made from petroleum oils. Oils will usually break down pretty well in alkaline chemical cleaners.

#### 1.1.1.2 Shop Dirt

Dust, shop dirt, and other forms of particulate can be removed with most alkaline or acidic cleaners and can also be removed by mechanical blasting or grinding, followed by a blow off.

#### 1.1.1.3 Carbon

Carbon is present in all organic compounds and in a few inorganic compounds. It is abundant in various steel alloys in the form of metal smut. Carbon smut is extremely inert and nonreactive due to electrostatic attraction to metal surfaces. Chelants do a very good job of breaking down smut whereas alkalis, solvents, and most acids are not very effective. Mechanical cleaning can also be very effective at removing smut from a steel surface.

#### 1.1.1.4 Oxidation

An oxide of any metal can develop on the metal surface right after the metal is formed or cast. Aluminum oxide and zinc oxides are white, while iron oxide is red rust. Copper oxide is recognized as a green tarnish. Acids are extremely good for the removal of oxides since all oxides are acid soluble. Some alkaline products that are not inhibited will remove zinc and aluminum oxides. Solvents are typically not effective. Mechanical cleaning is very effective for the removal of oxide layers.

Laser cutting is a commonly used process for many different gauges of steel. The laser cutting process creates an oxide layer on the edge that has been cut. Paint will adhere to the laser oxide but the laser oxide is not tightly adhered to the steel. If the coating is cracked along the edge it may completely delaminate, especially if the product is used out-of-doors.

Sanding, grinding, chipping, and blasting can be very effective for the removal of laser scale. Hand methods are somewhat limited due to the high labor content and the inherent inconsistencies associated with manual operations. Some shapes may be difficult to clean by hand.

Automated blasting can be very effective if the steel is heavy enough to withstand the pressure and all surfaces are accessible to the blast media. Blasting may be a good way to treat laser edge when hot-rolled steel (HRS) is used because the scale and other inorganic soils can also be removed.

Acidic chemical solutions have also been effectively used for the removal of laser oxide. Many of these solutions are phosphoric acid-based solutions applied by spray or in immersion systems. Phosphoric acid is aggressive enough for the task without over-reaction that may occur with some other acids.

The disadvantage of phosphoric acid is the significant volume of iron phosphate sludge, which, over time, without proper circulation and filtration, builds up in the tank, fouling heat exchangers, clogging plumbing systems, and eventually resulting in expensive system cleaning and downtime. In addition, in some cases, the strong acid solution will leave fine metal particles on the surface that show up in the coating.

In some instances, blends of acids are the most effective chemical approach. There are commercially available blends of acids that work synergistically to remove laser scale without many of the negative aspects of a single acid. In addition to selecting the proper chemistry, you must also apply the product properly. Adjusting cleaner concentration and bath temperature can optimize cleaning time.

It is very important to involve the chemical supplier for a wash system to make sure that the design for chemical removal of laser scale considers the compatibility of all the system chemistry with the process equipment's material of construction. Laser scale can be effectively removed when necessary using acid-resistant equipment and blended engineered chemicals.

#### 1.1.1.5 Wax

Waxes are similar in composition to fats and oils. Some are hydrocarbons, while others are esters of fatty acids. They are water repellent, nontoxic, smooth textured, and resistant to many chemical cleaning products. Waxes are often used on tubing as a rust inhibitor. They are solids at ambient temperatures so the cleaner used must reach the melting point of the wax to break it down. They are soluble in most organic solvents and alkaline cleaners, providing that the contact time is long enough and the temperature is high enough.

#### 1.1.1.6 Soaps

Soaps are sometimes formed by the water-soluble reaction of a fatty acid and an alkali. Soaps lower the surface tension of water and permit emulsification of fat bearing soils. Soft soaps, heavy metal soaps, and vegetable oil soaps can be found in products such as metalworking fluids. Alkaline cleaners are generally the best at saponifying soaps. Acids will turn the soap to a semisolid mass and make rinsing more difficult. Solvents are usually not effective, too expensive, and not environmentally desirable.

#### 1.1.1.7 Polymers

Polymers are sometimes used in compounds to provide good lubricity and releasing properties during certain manufacturing processes. Organic polymers can be natural, synthetic, and semisynthetic molecules such as phenolic materials and celluloses. Inorganic materials include siloxanes, silicones, and sulfurized polymers. Acids, alkaline cleaners, solvents, and detergents can be used to remove polymers.

#### 1.1.1.8 Silicone

Silicones are sometimes used as lubricants or release agents in manufacturing processes. Silicones can be liquid, solid, or semisolid. These are long, straight-chain polymers, very low in surface tension, and they are not easily broken down using alkaline or acidic products. They can be removed with organic solvents, but the solvent will become contaminated very quickly.

## 1.1.2 MECHANICAL CLEANING

As briefly discussed earlier, there are many types of soil on manufactured products, including organic substances such as oil or inorganic materials such as mineral-type rust inhibitors, scale, or rust. Many of these soils can be effectively removed by mechanically abrading the surface. Mechanical methods, including wire brushing, abrasive blasting, grinding, and sanding, are used to smooth as well as clean surfaces. Mechanical cleaning with a hand-held grinder or a manual blast system can be very effective, but it is very labor intensive. In-line blasting can be used to automate the process. Mechanical cleaning is sometimes the only way to remove excessive dirt, rust, or scale.

### 1.1.2.1 Blasting

Blasting with sand or grit will remove mill scale, rust, or previous coatings from a substrate and create a surface profile that provides good coating adhesion. The dry film thickness of coatings used over a shot-blasted substrate is determined by the profile produced. A general rule of thumb would be 1 mil over the peaks of the profile. Thicker films are recommended, if the part will be used in an outdoor application.

Blasting operations can be manual batch systems or automated in-line systems. Blasting systems can use high-pressure nozzles or a centrifugal wheel to deliver the blast media. Nozzle blast systems require compressed air for delivery of the media, while a wheel system uses centrifugal force. Even though the compressed air is an added cost, it may be necessary to direct nozzles into hard to reach areas of a part. The blast area must be enclosed to contain the blast media and dust.

A blasted surface will create a very good anchor pattern for a coating. A blast system does not require as much space as a spray washer. Chemical use, maintenance, and the associated effluent are avoided. Mechanical treatments may be the only treatment required for finishes, where initial coating adhesion is the only critical requirement. However, mechanical cleaning alone will not provide undercoat corrosion resistance or extend the life of the finished product. Adequate coverage with the coating material is critical, if extended life is expected over a blast-only surface. The film thickness of the coating on a blasted surface must be thick enough to cover the peaks and valleys of the anchor pattern created by the abrasion.

Handheld air-blast systems are very dependent on the concentration of the operator, and the quality may vary. Blast cabinets are often suction-feed systems that draw particles into the spray gun by induced vacuum and accelerate the media with a metered stream of compressed air. Pressure-blast systems use a pressurized vessel to deliver the media, providing higher nozzle velocity that can clean the surface much faster than a suction system.

Blast cabinets function similar to any booth designed for containment of oversprayed material. Negative pressure within the cabinet is maintained with a fan that draws air into the enclosure through a suitable filter. Typically, this exhaust system will use a cyclone separator to remove the dust and fine particles from the airstream and recover the media for reuse. The scrap material that is separated out of the airstream is collected for disposal in a container attached to a dust collector. This scrap material should contain a small percentage of the heavier, reusable media to indicate that the fan pull is sufficient to prevent the buildup of fines in the recovered blast media. A vibratory screener can be added to the process to further refine the recovered material and maintain consistent particle size.

Turbine-blast systems use high-speed turbine wheel with blades. The media is metered to the center of the wheel where it is fed onto the blades, which sling the particles at the surface being blasted. These systems are more energy efficient than air-blast systems, because they do not use compressed air for delivery.

Abrasive blasting is most often used for the preparation of heavy structural parts, particularly HRS welded components. It does an excellent job of removing rust, smut, carbonized oils, and inorganic surface contaminants that are characteristic of this type of product. It can also effectively remove organic soils as long as the blast media is maintained to avoid a buildup of oil that can cause contamination. The blasting dust needs to be washed away or blown off before the coating is applied.

Different blast media can be used to vary the profile created on the metal surface. Less aggressive media will remove most soils without cutting too deeply into the metal and leaving a visible texture on the metal surface. More aggressive media can be used to cut stubborn encrustations, such as red oxides, but it will leave more texture on the surface.

A blast system requires less space than a spray washer that uses chemical cleaning and it does not generate any wastewater. Mechanical cleaning may be the only treatment required for finishes where initial paint adhesion is required. However, mechanical cleaning alone will not provide undercoat corrosion resistance or extend the life of the finished product.

The degree of cleaning with the blast operation depends on the quality requirements of the surface. Published documents clearly define quality grades of blast-cleaned steel surfaces. Pictorial standards were originally developed by the Swedish Corrosion Committee and later adopted by the Steel Structures Painting Council (SSPC) (Table 1.1) and other organizations. The principal four grades of blasting endorsed by the SSPC are as follows:

*White metal blast*: Removal of all visible rust, mill scale, paint, and foreign matter. Used for conditions where corrosion resistance is very important and the environment is highly corrosive.

*Near white metal blast*: Blast cleaning until at least 95% of all surface area is free of all visible residues. Used for harsh environments where product is exposed to heavy usage.

*Commercial blast*: Blast cleaning until at least two-thirds of the surface is free of all visible residues. For applications where tightly adhering contaminants are allowable on the surface; used for products with lower quality standards and noncorrosive environments.

**TABLE 1.1**
**Metal Blast Standards**

| Degree of Cleanliness | SSPC Standard | NACE Standard |
|---|---|---|
| White metal blast | SSPC-SP 5 | NACE No. 1 |
| Near white metal blast | SSPC-SP 10 | NACE No. 2 |
| Commercial blast | SSPC-SP 6 | NACE No. 3 |
| Brush of blast | SSPC-SP 7 | NACE No. 4 |

For additional information on blast cleaning standards: Plaster, H.J., *Blast Cleaning & Allied Processes*, Vols. I and II, Industrial Newspapers Ltd., London, 1973 and Fuchs, F.J., "Abrasive Blasting Systems," in *Metal Finishing Guidebook & Directory*, Vol. 95, No. 5A, Metal Finishing, Hackensack, NJ, 1997, p. 49.

*Brush-off cleaning*: Blast cleaning of all except tightly adhering residues of mill scale, rust, and old coatings, exposing numerous evenly distributed flecks of underlying metal. Acceptable in noncorrosive environments where long-term coating life is not expected.

The Swedish Standards Association (SIS) includes good equivalents of these standards. The British Standards Institute (BSI) also includes very close equivalents of the first three of these standards. The National Association of Corrosion Engineers (NACE) has also developed a set of encapsulated steel coupons that simulate the four degrees of cleanliness (Table 1.1).

### 1.1.2.2 Blast Media

The blast media affects the depth of the blast profile and surface roughness after blasting. Blast media can be made of natural material such as silica, sand, mineral sand, flint, garnet, zircon, and other mineral products. Some natural by-products are also used for blasting, such as walnut shell or corncob. Other blast materials are manufactured using a variety of metal and nonmetal compositions such as steel, iron, aluminum oxide, silicon carbide, plastic, wheat starch, and glass bead.

The size of the media particles will affect the blast pattern. Other media selection criteria include how well it will cut, how well it will recycle, and how much it cost. It is also important to know if there are any health and safety issues, such as lung problems associated with silica, and if the media will leave by-products on the surface, such as oils from walnut shells. Table 1.2 shows some common blast media and their comparative characteristics.

In addition to the comparative issues listed in Table 1.2, it is a good idea to test different media to have a visual idea of the effect that they will have on the part.

Hard grit media such as aluminum oxide will cut faster and deeper than soft, angular media such as plastic or agricultural grit. Mineral, ceramic, or metallic grit media are used in air-blast systems. Iron and steel media are more often used in turbine-blast equipment.

## TABLE 1.2
## Comparison of Blast Media

| Material | Mesh Size (US) | Shape | Density (lb/ft$^3$) | Mohs (Hardness) | Friability (Breakdown Factor) | Initial Cost | No. of Cycles | Cost per Use |
|---|---|---|---|---|---|---|---|---|
| Silica sand | 6–270 | A, S | 100 | 5.0–6.0 | High | Low | 1 | Med. |
| Mineral slag | 8–80 | A | 85–112 | 7.0–7.5 | High | Med. | 1–2 | Med. |
| Steel grit | 10–325 | A | 230 | 8.0 | Low | High | 200+ | Med. |
| Steel shot | 8–200 | S | 280 | 8.0 | Low | High | 200+ | Low |
| Aluminum oxide | 12–325 | A | 125 | 8.0–9.0 | Med. | High | 6–8 | Med. |
| Glass bead | 10–400 | S | 85–90 | 5.5 | Med. | Med. | 8–10 | Low |
| Plastic | 12–80 | A | 45–60 | 3.0–4.0 | Low/med. | High | 8–10 | Med. |
| Wheat starch | 12–50 | A | 90 | 2.8–3.0 | High | High | 10–12 | High |
| Corn cob | 8–40 | A | 35–40 | 2.0–4.5 | Med. | Low | 4–5 | Low |

A = angular product that cuts more sharply; S = spherical product that peens and does not cut as sharply; Med. = medium.

Materials that are more prone to fracture, reflected in the chart by friability, are not good materials for recycling, because the particle size is reduced during the blast process and the media may not be of sufficient size and sharpness to cut soils from the surface. The recirculated material will not be as effective, and the surface will vary widely after blasting.

#### 1.1.2.3 Vibratory Cleaning or Tumbling

Vibratory systems use an abrasive media in a cleaning solution to remove burrs, rough edges, and surface contamination. They can be useful for preparation of small castings or parts that have trim die flash or rough edges. They will remove the roughness and dried-on compounds that are often present on a cast surface or the burrs left behind on a sawed edge. Vibratory cleaning will leave some residue on the surface, and it is a good idea to spray clean parts after the vibratory polishing so that and residual cleaning compound is removed before coating.

### 1.1.3 CHEMICAL CLEANING

The first step in the chemical pretreatment process is the removal of dirt, oils, and other soils that could cause surface defects, interfere with the development of a good quality conversion coating, or interfere with paint adhesion. Chemical cleaning methods include wiping the part with a rag, dipping the part into a solution, or using a spray cleaning system. The cleaner may be alkaline, acidic, neutral, solvent, or an emulsion. The particular cleaner and process used will depend on the soils to be removed, the size and substrate material of the part, the type of coating to be applied, and the quality goals for the product.

### 1.1.4 CHEMICAL CLEANING PROCESSES

The different methods of chemical cleaning have certain applications where they fit and limitations that make them unsuitable for other applications. A review of the various methods of applying a chemical cleaner helps to understand these strengths and limitations.

#### 1.1.4.1 Hand Wipe

The most inexpensive method of cleaning from an equipment perspective is manual cleaning of parts. This would normally involve hand-wiping parts with a solvent or aqueous (water based) cleaning solution. Manual cleaning can be somewhat effective in terms of soil removal but is very costly in terms of labor and very slow in terms of production time. Because of this, hand-wiping of parts is rarely done except on a spot basis.

Hand wiping with a clean cloth does not require any capital investment, but it is not very effective at soil removal; it has a high labor content, is inconsistent, and may create health and safety problems.

#### 1.1.4.2 Immersion Cleaning

Cleaning by immersion in solution is often used for small parts in a batch system. Immersion systems can be either static (still) or agitated. Immersion cycle times are typically longer than spray cleaning methods, because spray systems have the added cleaning power of mechanical energy from spray pressure. Systems with no agitation require longer cycle times, and they are not as effective.

Agitated immersion systems have the added benefit of physical movement between the solution and the parts being cleaned. This aids in the overall speed of reaction taking place between the cleaning compound and the soil. Agitation may be achieved in the tank through air addition or blade mixing. Some dip systems may also use a hoist to lift a basket of parts up and down in the tank to provide agitation. Dip systems normally require higher chemical concentration than spray systems and longer operation times, even with agitation.

When the parts are lifted up from the chemical solution, they may retain some residual chemicals or oil that may float to the surface of the solution. Cleaners used in dip systems should be products designed to emulsify oils rather than products that disperse the oils and allow them to float to the surface.

Many systems use some immersion cleaning along with spray stations. Automotive systems often include some immersion stages to make sure that all of the surfaces of the product are fully wetted and dirt is loosened inside and outside of the part. The use of immersion with spray stages can enhance overall performance.

#### 1.1.4.3 Hand-Held Spray Wand

Handheld spray wands or steam spray systems are often used to clean parts in a batch powder coating operation. A manual operator has the time to focus attention on stubborn soils and hard-to-reach areas, providing very thorough removal of soils. Spray wands are often used for larger parts that cannot be easily transported through automated systems.

The spray wand is used inside a booth. The booth encloses the process so that the water vapors is captured and exhausted to atmosphere. Over-sprayed solution can be run straight to drain or captured, filtered, and reused. As in manual wiping, this process is time consuming and is not efficient for large numbers of small parts.

High-pressure spray wands can use hydraulic pressure as the force to do the cleaning. This type of cleaning is done at pressures ranging from 400 to 1000 psi. The temperature ranges from cold water to hot water (200°F) for high-pressure washing. This type of washing is done with or without cleaning compounds. The water volume used ranges from 2 to 35 gal/min.

Steam generators are sometimes used to produce dry saturated steam for spray cleaning. In a coil-type, forced-circulation steam generator, water is forced into the coil toward the discharge point. As the water passes through the coil, it becomes progressively hotter as steam is formed. Most of the water is evaporated before it discharges into the steam generator. This type of steam generator is designed to circulate more water than is evaporated. This excess water carries loose scale particles and other foreign matter through the coil and into the separator. Here, the water and scale particles are separated from the steam, providing high-quality, dry, saturated steam.

Steam systems are not as effective as hot-water systems. They do not provide as much energy at the parts surface and do not wet out the surface as well. The energy required to generate steam is higher than the hot-water systems.

Spray wand systems provide flexibility for contact time and angle and the high pressure can remove heavy greases. Higher foaming surfactants may be used, because foam is generally not a concern and higher temperatures are possible, so it may be easier to melt waxes and grease.

The labor content and the chemical cost are high. Cycle times are long, and spray wands are not suitable for higher volumes of small parts. Spray wands do not offer the wide variety of chemicals and process steps that are possible with multistage spray washers.

### 1.1.4.4 Ultrasonic Cleaning

Ultrasonic cleaning utilizes high-frequency sound waves to increase the effectiveness of the cleaning chemicals and the agitation at the soil–substrate interface on the material. Transducers are located either inside or outside the cleaning vessel to produce the sound waves. When the sound waves reach the surface of the material to be cleaned, they cause cavitation. Cavitation is the formation and collapse of vapor bubbles and voids in liquid by acoustic energy at high frequencies. These tiny exploding bubbles act as a brush to carry particles and used chemical away from the surface of the substrate. This increases the capabilities of the chemicals by continuously replacing inactive, reacted product, with fresh chemical. In addition, it gives the chemicals new sites to work on by breaking away loose dirt and other contaminants.

Metals are the best candidates for ultrasonic cleaning, since their crystalline molecular structure allows vibration to occur relatively freely. Rubbers and plastics do not work nearly as well, because the molecular structure of these materials is more likely to absorb the shock waves rather than vibrate with them.

Ultrasonic cleaning works very well for cleaning metal surfaces and they are multimetal safe. Complex geometries and blind holes do not diminish the effectiveness of the sound waves since they clean the part throughout; these are not line-of-site devices. The consistency of ultrasonic cleaning is much higher than conventional cleaning methods as well. Cleaning occurs on all surfaces of the object for the entire duration of the process. Ultrasonic is particularly effective for some porous metals such as bronze.

Larger loads do not clean, as well as smaller loads, given the same time frame, due to energy absorption. Large, heavy parts can block each other out and cause poor cleaning.

### 1.1.4.5 Recirculating Spray Washers

Spray washers are the most common way to chemically clean and treat a part for application of a coating. A spray washer uses a series of spray stages that feature different solutions for different tasks. Each stage of a spray washer consists of the solution tank, the recirculating pump, plumbing for delivery of the solution, a tank heating system, and the gauges and controls that operate the system. A tunnel is mounted over the tanks to contain the spray process. Parts are usually transported

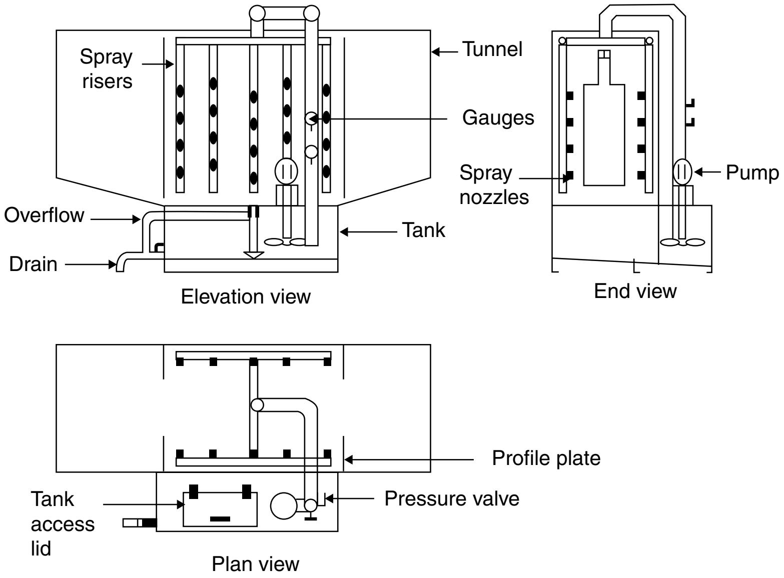


FIGURE 1.2 Spray washer components.

through the washer tunnel on an overhead conveyor, although smaller parts washers may use a belt-type conveyor. The cleaning solution is recirculated through the spray header up to the risers and out through nozzles onto the parts. The parts of the spray washer are shown in Figure 1.2.

The nozzles on the risers aid in the cleaning process by providing a directed pressure spray in a predetermined pattern to completely cover the part. The most common nozzle used in this application is the vee-jet, which produces a flat, fan-shaped spray of uniform density. The angle of spray (20°–90°) is determined by the nozzle and riser spacing in the washer stage and the desired level of overlap in the spray pattern. As seen in Figure 1.2, the nozzles are placed so that all surfaces of the part are reached as it proceeds through each of the various stages.

The recirculating spray washer is the most efficient process for continuous production flows. It can handle large volumes of products and provide excellent cleaning and treatment of most parts.

Spray washers are significantly more expensive than manual cleaning methods and they also cost more to operate. They require more maintenance and control to perform properly.

The number of stages of a spray washer depends on the substrates to be processed, the type of cleaning and other processes that will be used, space availability, and cost. The end use of the part and the performance requirements of the coating will also impact the number of stages. Generally speaking, more stages will improve cleaning and finish performance.

Three-stage washers are common for products that do not need exceptional corrosion resistance. The first stage is normally a cleaner or cleaner/conversion coating followed by two rinse stages. The rinse stages are usually recirculated water rinses with a volume of water (typically 3–5 gal) overflowed to drain and made-up with fresh water to maintain relatively clean rinse water. The cleaner stage is usually heated to enhance the performance of the cleaning solution. Rinses are not typically heated, although the final rinse is sometimes heated to leave the part surface warm and accelerate drying after wash.

Stepping up from three stages of pretreatment to five stages allows the separation of the cleaning and the conversion coating steps, with a rinse in between each process to reduce cross-contamination of the cleaner and conversion coating solutions. As washers increase in complexity from five- to seven-stage systems, the added stages are generally additional cleaners or rinse tanks. Good cleaning is an essential part of the pretreatment process. Excellent rinsing ensures that the residual chemicals and soils are removed before the coating is applied.

Proper cleaning of some parts may require a combination of spray and immersion stages. The spray stage combines the chemical properties of the cleaner with the impingement action of the solution applied under pressure. Immersion penetrates areas of the part that may be inaccessible to the spray and improves wetting of hard to reach surfaces.

### 1.1.5 COMMON INDUSTRIAL CHEMICAL CLEANERS

The selection of the correct chemical product for an application is critical to the proper operation of the cleaning system. Products typically used in pretreatment include alkaline cleaners, neutral cleaners (which also act as detergent additives), acid cleaners, and solvent emulsion cleaners. In each group, there are specific attributes to be considered. The cleaner selected must have the ability to remove a wide variety of soils, prevent redeposition, provide cleaning even when contaminated, provide foam control, be easily rinsed, and be cost effective.

Cleaners are often classified according to their pH. The pH of the solution is a measurement of the relative alkalinity or acidity. On the pH scale, pure water is neutral and has a pH of 7. A pH below 7 is considered acidic and above 7 is alkaline. Caustic soda has a pH of 13 or 14, while hydrochloric acid has a pH of less than 1. A typical range of pH is shown below.

- Alkaline cleaners—mild, pH 9–10.5
  — medium, pH 10.5–11.5
  — high, pH > 11.5
- Neutral cleaners—pH 6.5–9
- Acid cleaners—pH 1.0–5.5

The various components that are used to build an industrial cleaner have their own unique mechanisms that affect certain soils.

#### 1.1.5.1 Alkaline Cleaning

Alkaline cleaners are popular for metal cleaning operations, primarily because of the versatility of their components and their ability to break down organic soils.

Most of the soils that commonly occur in metal processing can be effectively removed by the correct selection of these individual components. The most important elements are the alkalinity source and level, the addition of chelants or chelating agents, and the surfactants.

The key to an alkaline cleaner is the source of alkalinity selected for the formulation. Alkalinity source selection considers both free and total alkalinity.

Free alkalinity refers to the material in the solution that is easily reactive. It can be either sodium or potassium hydroxide-based. Sodium hydroxide (NaOH) is very reactive with organic soils such as animal and vegetable fats and is saponifiable (able to be reacted with free alkali to form water-soluble materials). As sodium hydroxide tends to cause some rinsing difficulties because of its affinity for metal, the slightly less reactive potassium hydroxide (KOH) is sometimes used to create a product that is easier to rinse. Products having high levels of free alkali (NaOH or KOH) are good cleaners for products with heavy deposits of organic materials.

In some cases, high levels of free alkalinity are not desirable. Hydroxide-based products can attack some metals, such as aluminum, resulting in etching or dissolving of the metal. Alkaline builders, actually alkaline salts such as carbonates, phosphates, and silicates, are often used to clean these metals. These builders contribute to total alkalinity and they often have other properties that contribute to more than just alkalinity. For example, silicated products that are normally considered to be aluminum safe can be used to form a protective barrier on the metal to prevent further oxidation/attack by the alkalinity of the product. Silicates are also effective dispersants for particle soils. Phosphates also help to disperse particulates and aid in tying up water hardness.

Caustic is a generic term for hydroxides. Sodium hydroxide, which provides the highest level of free alkalinity, is very effective at saponification but tends to resist free rinsing. Potassium hydroxide provides better rinsing, but is slightly less effective than sodium hydroxide. Caustic gives the most alkalinity punch for the pound of any of the alkalinity sources. Caustic also creates a water-soluble soap from the previously nonsoluble oil or fat.

Sodium hydroxide (NaOH) is cheap and plentiful. Caustic soda, or sodium hydroxide, is often used for pH adjustment (to raise pH). Sodium hydroxide is used in many cleaning compounds, electro-cleaning products, and alkaline-based paint strippers.

Potassium hydroxide (KOH) is more expensive, more soluble, and freer rinsing than sodium hydroxide. It is still high in free alkalinity and offers excellent soil saponification.

Carbonates are a less potent source of alkalinity than hydroxides but one that will still provide some degree of saponification of oils and fats. They are often used as a base for mild alkaline cleaners. Sodium carbonate, also called soda ash, is also used for pH adjustment, especially when a lower level of alkaline pH is desired. One of the major disadvantages of carbonates is their tendency to form calcium carbonate scale in high temperature and hard water conditions.

Sodium meta-silicate is used for several purposes in cleaning formulations. It contributes alkalinity, and it can provide limited saponification. It has excellent particle soil dispersion capabilities and prevents particulate matter from redepositing on an already clean surface in an aqueous environment. Silicate inhibits attack on aluminum and zinc surfaces by plating out on the metal surface as soon as the clean surface is available to protect the clean surface from high alkaline attack.

Phosphates serve several roles in a cleaner formulation, including alkalinity building, pH elevation, saponification, and particulate soil dispersion. Phosphates are especially effective where smut and other particulate soils are encountered. Phosphates come in many forms from the polyphosphates to orthophosphates.

Tri-sodium phosphate (TSP) is used in development of orthophosphates. TSP is moderately alkaline, moderate on particulate soil removal, moderate for oils and greases, and has some limited dispersant capabilities.

Two sources are typically used for complex phosphates; they are sodium tri-polyphosphate (STPP) and sodium hexametaphosphate. Complex phosphates are excellent sequestrants, complexing calcium to act as a chemical water softener. It has excellent particle soil removal capabilities (pigments, for example) and very good particulate soil dispersion capabilities.

It is a good corrosion inhibitor for ferrous surfaces and functions as a threshold scale inhibitor. Polyphosphates are, however, environmentally objectionable in some areas.

Chelants are often added to alkaline cleaners to aid in the removal of particulate soils such as carbon smut or metal fines. Chelants are compounds, which tie up metal ions, allowing them to be dispersible in water. Chelating chemicals can be inorganic materials, such as ethylenediamine tetraacetic acid (EDTA), or organic materials, such as citric acid. Chelated products are often required when cleaning metals with high carbon content, such as steel that has been hot-rolled or metals that have undergone processes, which may have contributed particulates, such as drawing or lapping compounds. Chelants are not often used on aluminum because of attack on the metal, so most aluminum-safe products will be chelant-free. Chelants can also cause some problems in plants, where waste recovery of heavy metals (such as lead) is carried out in-house. Common chelating agents include EDTA, sodium gluconate, and organic acids.

EDTA is extremely free rinsing and exceptionally effective as a chemical softener when high levels of calcium and magnesium are present in the water. In alkaline products, EDTA is also very effective on taking off light surface rust. Sodium gluconate is used in formulating most hot tank paint strippers, because it is particularly stable and effective on paints. Paint pigments are often metallic-based, and sodium gluconate helps to pull them off and keep them dispersed in solution. Organic acids are used in acidic formulations. Common organic acids used include citric acid, ascorbic acid, acidic acid, hydroxy-acidic, and formic acid.

Typically, a mild alkaline cleaner (pH of 9–10) will provide better soil removal and longer bath life than a high caustic solution. Residues of alkali salts will kill the free acid, drop out metal salts, and kill the phosphate bath. High caustic can also be too aggressive in attacking zinc and aluminum surfaces, possibly creating smut and adding zinc to the solution. A mild alkaline cleaner prior to the phosphate stage will aid in the formation of a more uniform, dense phosphate coating, leading to better paint adhesion and corrosion protection. If the cleaning is not adequate, it is usually better to increase the time in the cleaner rather than the concentration. Two mild alkaline cleaner stages are better than one high caustic stage. Mild alkaline cleaners are good for multiple metals and they can be run at a wide variety of temperatures. In some cases, a higher pH cleaner may be necessary on occasion for very difficult soils.

A list of the functions of different alkaline cleaner components is shown below.

- Silicates—(sodium metalicate, sodium orthosilicate) High alkalinity, good saponifier and dispersant, softens water by precipitation, inhibits dissolution of zinc and aluminum. May leave a whitish residue on parts, if not properly rinsed
- Phosphates—(TSP, STPP, tetrasodium pyrophosphate, disodium phosphate) Softens water alkalinity, improves rinsing, saponifier
- Carbonates—(sodium carbonate, sodium bicarbonate) Alkalinity, good buffering
- Hydroxides—(sodium hydroxide, potassium hydroxide) High alkalinity, saponifier
- Nitrites—(sodium nitrite) Minimizes oxidation of metal due to cleaner drying
- Chelants—(versene) Softens water, changes form of precipitation
- Surfactants—Provide water/oil solubility. Enable cleaners to work more efficiently by reducing surface tension at the metal surface. Also, prevent part from drying between stages or the spray washer
- Defoamers—Control foam
- Inhibitors—Minimize attack on metal

The alkaline cleaner is added to water (typically 2–10%) and applied hot. Solutions of this type have low surface tension, which means they can easily penetrate beneath and between dirt particles. In addition, the soap or detergent present can often combine with dirt, oil, or grease and emulsify them in water to remove them from the surface of the part. When used with pressure spray or mechanical scrubbing, hot alkaline cleaning for 1–2 min is a very effective cleaning method.

#### 1.1.5.2 Neutral Cleaners

Cleaners with a neutral pH are basically surfactant-based formulas without the addition of alkaline materials. These can be used alone in cases where only light soils or nonsaponifiable soils are present. Often, they are used as cleaning boosters in combination with an alkaline or acid cleaner or a phosphatizer where additional cleaning is required.

#### 1.1.5.3 Acid Cleaners

Acid-based cleaners are typically used for special applications in metal cleaning, such as weld-smut or rust removal. In these applications, the base acidity, combined with additives such as organic chelants, is doing most of the cleaning through removal of deposits from the metal. Surfactants can be built into acid cleaner formulations, but the choice of surfactants active at an acidic pH is somewhat more limited than alkaline cleaners.

Acids include a number of chemicals that are acidic when dissolved in water (lower than 7.0 on the pH scale). Acids are typically especially good on removing metal oxides and are also typically better cleaners where high levels of smut are encountered, such as on hot-rolled metal.

Some common acids used in industrial cleaners are phosphoric, hydrochloric, sulfuric, hydrofluoric, and sulfamic.

Phosphoric acid is a primary building block of many acid-based products. It does a good job of contributing to smut removal with a relatively mild attack of the metal. It is also the primary source of phosphate in phosphating solutions.

Hydrochloric acid, also commonly referred to as muriatic acid, is a very aggressive and corrosive mineral acid. It is used extensively in descaling and rust removal operations where a very strong, aggressive acid is needed to remove heavy rust. Hydrochloric acid is also frequently used for pickling operations and mill scale removal.

Sulfuric acid is another aggressive acid that is used primarily for pickling ferrous metals and mill scale removal. It is often used to neutralize alkalinity prior to discharging alkaline solutions to sewer and is a very effective calcium carbonate scale remover.

Nitric acid is an extremely aggressive acid with limited use in industry. Its primary use is in the passivation of stainless steel, where it preferentially dissolves the iron away from the chromium on the surface. The remaining top metal layer, being exceptionally rich in chromium, is then polished to achieve a very dense, high chromium stain resisting surface on the metal.

Hydrofluoric is an extremely aggressive acid used primarily in industry for the brightening of aluminum. Hydrofluoric acid has the ability to remove the very dense and tenacious oxide coating, which forms on aluminum surfaces. It is also used in the etching of glass. Hydrofluoric acid is sometimes used as an additive to phosphate solutions to activate them for prepaint preparation of aluminum surfaces. Hydrofluoric acid is extremely dangerous. It is extremely corrosive to skin and mucous membranes.

Sulfamic acid is primarily used in descaling. It is much safer to handle than a liquid hydrochloric acid. It is also particularly good at dissolving old corrosion products. It is highly soluble in water and its end-use temperature should be kept below 140°F.

### 1.1.6 SURFACTANTS

Surfactants (surface active agents) are short-chain organic polymers that are lipophilic (fat/oil-loving) at one end of the molecule and hydrophilic (water-loving) at the other. This unique construction gives them the ability to penetrate and stabilize oils and greases in a water environment. The lipophilic end of the molecule is attracted to oils and greases and, in turn, allows the dispersion of these captured oils due to the attraction of water to the other end. Oil is broken into droplets, which can then form an emulsion in the water solution or split out from the water, floating to the surface, depending on the surfactant type chosen.

Cleaning compounds often have 1–5% surfactant(s). Surfactants act as penetrating agents, wetting agents, emulsifiers, suspension agents, and coupling agents.

Soaps, natural anionic surfactants, are made through a process called saponification, reacting fatty acids with caustic soda. Soaps are typically high-foaming materials and good oil emulsifiers, but are unstable in acidic conditions.

Anionic synthetic detergents provide excellent penetrating and wetting properties, but they are high foamers and are relatively poor at suspending soils.

Cationic synthetic detergents are low foamers, but are relatively poor cleaners, with little detergency. Cationic materials are sometimes used as emulsifiers.

Amphoteric synthetic detergents are low foaming at most temperatures but are not particularly good soil dispersants or stabilizers. The key feature of amphoterics is their ability to penetrate soils.

Nonionic synthetic detergents do not have a plus or minus charge and are the most broadly used. They are not as good at penetrating and wetting as the anionics are, but they are excellent soil stabilizers and emulsifiers. They can be low to high foamers depending on their cloud point and pH. Cloud point is the temperature at which a nonionic surfactant loses solubility, partially comes out of solution, and functions at the water surface as an active defoamer. Cloud point is the temperature above which a nonionic-based detergent can be used in a recirculating spray washer. Nonionic surfactants are most active within a 10–20°F range on either side of the cloud point. For this reason, most nonionic-based detergents are formulated using several carefully chosen nonionics to provide good detergency and low foam over a wide range of temperature.

A typical spray cleaner stage in a washer is 60–90 s. A dip stage may be anywhere from 3 to 5 min with temperatures ranging from 120 to 180°F. Times, temperatures, and cleaner concentration vary depending on the cleaner used and the condition of the substrate.

The rinse stage following the cleaner is ambient tap water to remove any residual alkaline cleaner or loosened soil. Rinse stages are overflowed with fresh water as parts are processed to continuously reduce the soil buildup in the water.

Cleaning and rinsing alone prior to coating is sufficient as a stand-alone pretreatment in a limited number of situations. Like mechanical cleaning, initial adhesion can be good, but without a conversion coating the product does not have any long-term corrosion protection.

When cleaning prior to conversion coating, it is important to consider how the cleaner and its effect on the substrate may interfere with the formation and deposition of the conversion coating. Chemical solutions must be isolated by proper drain time and rinsing to prevent transfer of residual chemistry from one stage into another. If a significant amount of chemical is carried from one solution to another, it may interfere with the performance of the washer and add cost to the operation. In a pretreatment process, the cleaner should not be viewed as a separate process but as an integral part of the total pretreatment process that can affect the quality of the conversion coating.

### 1.1.7 FACTORS THAT AFFECT THE PERFORMANCE OF THE CLEANER

The key factors that affect cleaner selection include soil, substrate, quality goals, and method of application. Three other important issues that must be addressed prior to selecting a cleaning product are the quality of the incoming water, the cost of the cleaning products, and compliance with local regulatory rules.

#### 1.1.7.1 Quality of Water Supply

Whether drawing from a well or tapping into a municipal water supply, the kind of water you use can impact chemical performance and finished goods quality. Some of the most common constituents of water you should manage are as follows.

Water hardness and the inverse solubility of calcium and magnesium ions, particularly in the presence of carbonates, can lead to problems such as scale buildup. Layers of scale in the piping can restrict flow and contribute to the plugging of nozzles. Scale buildup also reduces the efficiency of heat exchange surfaces and increases energy consumption dramatically.

Hard water can also cause spotting on part surfaces and it can reduce the effectiveness of some detergents, because they will react with the minerals in the water instead of the soils on the part.

Water hardness can be controlled with mechanical methods such as water softening (ion exchange) or deionizing (dissolved solids removal). The cost of the equipment for softening the water can be recovered by the savings in improved production quality, reduced energy use, and reduced chemical use.

Chemically, water hardness can be “tied-up” by complexing these ions with a more soluble agent like certain phosphates. In addition, holding these metals in a soluble state with chelating agents will eliminate most of the problems they create.

Some water supplies will have a higher concentration of iron, especially if the water is supplied from a well. Excess iron can cause streaking and staining on the substrate. In addition, deposits of iron can create corrosion cells on the part surface and possibly lead to premature corrosion on ferrous metal surfaces. Iron can be removed with ultra-filtration, chelants, precipitation, or deionizing systems.

Silica in the water can be a problem for pretreatment systems. High levels of silica, from incoming water or the manufacturing process, can create a glass-like film that is very hard to remove and substantially reduces heat transfer efficiency. Filming on parts, especially glass and plastic, may interfere with subsequent processing of parts or their finished quality.

High levels of bacteria in the water supply can cause rapid slime growth in tanks and raise the level of dissolved solids in solution. This can result in contaminated parts that can show up as corrosion under a coating and it can also cause increased levels of foaming in a solution. Iron reducing bacteria can cause deterioration of process equipment.

The incoming water should be monitored to develop a standard for supply water. Variations from the standard may show that the local supply has not been adequately treated. If a well is used and bacteria levels are beyond the acceptable range, cleaning of incoming water is necessary. If a cleaning solution or rinse has gone bad due to bacteria growth, the process should be thoroughly cleaned, sanitized, and rinsed.

The selection of a cleaner is based on the soils to be removed, the substrate, and other variables. The performance of a cleaning solution depends on proper adjustment and maintenance.

#### 1.1.7.2 Soils in Solution

Soils that are removed from the parts will build up in the cleaner solution over time. Solid particles will settle to the bottom of the tank as sludge and oils, grease, and some floating debris will float on the top of the solution. There is a limit to the amount of contamination that a cleaner bath can tolerate before it will cease to clean and need to be dumped and recharged. Overflowing the solution can help to reduce the accumulation of floating debris, but solids can still cause a problem and overflowing the solution will create a need for more chemical. Oil skimming and sludge removal can extend the life of the cleaner and techniques for this are explained in the section of this book on washer design.

Certain operating parameters need to be controlled for good performance. The control parameters that affect the performance of the cleaner include contact time, chemical concentration, temperature, spray pressure, drain time, and the volume of contaminants in the solution. These are the items that must be monitored, recorded, and maintained within proper ranges in order to achieve predictable cleaning performance.

#### 1.1.7.3 Time

It is important to have enough contact time to provide complete wetting breakdown of soils. The longer the contact time, the more the reaction will be. The control of contact time is usually equipment related. If the cleaning method is manually operated, the time can be adjusted for different soil loads. If the cleaning system is automated the time will depend on the conveyor line speed.

#### 1.1.7.4 Temperature

As a rule of thumb, cleaning chemical processes can be accomplished more quickly with higher temperatures. The chemical supplier will recommend a temperature range needed to provide satisfactory performance with their product. With some cleaners, elevated temperatures can adversely affect substrates and chemical compounds. Improper temperature may also cause excess foaming with some cleaner products. Managing the temperature requires a properly maintained thermostat and heating source (boiler, heating elements, burners, etc.).

#### 1.1.7.5 Spray Pressure

The physical force of solution under pressure, agitation in a chemical solution, or scrubbing will enhance the performance of a cleaning solution. This factor is extremely important in removing tough soils such as particulate matter and heavy buildup of grease and oil.

Controlling the scrubbing force in a system depends on the method of application used. In the case of spray systems, it is important to keep the nozzle orifices clear of scale and shop debris to help maintain the proper pressure. Immersion systems or dip tanks can use air agitation, solution circulation systems, or a mixer blade.

#### 1.1.7.6 Concentration

Chemical concentration is related to the particular product being used. Concentrations should be consistent with the suppliers' recommendations. Too much cleaner may cause poor rinsing or excess carryover. If the concentration is too low, the parts may not get adequately cleaned.

The substrate, types of soils, and the equipment used all influence chemical selection and solution strengths. Certain blends of chemicals work well for immersion systems but not in other applications. Problems may occur in the degree of reaction, flash rusting, or foaming. Concentration control is very important. Cleaning solutions should be monitored regularly and controlled. Simple titration is typical, using either dropper or burette techniques.

The effectiveness of a cleaner solution gradually decreases as the soil load builds up. The effective life varies depending on hours of operation, the volume of metal processed per hour, the type of metals processed, the amount of carry out, the use of filtration, and the types of soils removed.

### 1.1.8 METHODS USED TO MEASURE CLEANING RESULTS

The cleanliness of the substrate will have a big impact on subsequent treatments and the ultimate performance of the coating. It is very important to keep track of cleaner performance. Visual inspection is useful as a routine part of supervising the operation, but it is subjective and does not provide any data to confirm the results. Still, if a product does not look clean, it probably is not.

Wiping the surface with a clean white cloth is good for determining the presence of inorganic and particulate matter, such as carbon smut, that oftentimes does not show up until substrates are cleaned. It is not a perfect test as some phosphate coatings may leave some minor smut without interfering with performance, but it does help to monitor daily operation.

Parts should be routinely observed as they exit the washer to see if the water beads up or sheets off in a "water-break-free" condition. A water-break-free condition indicates an absence of organic materials that could interfere with adhesion and ultimate performance.

Another qualitative test aimed at determining if soils remain on a part after cleaning is the scotch tape test. Clear adhesive tape is laid on a part and rubbed firmly over the surface; when pulled back, the "sticky" side will have particulate matter attached to it that can be viewed and referenced. Besides providing a relative degree of cleanliness, this test will measure the degree of adherence of soil such as carbon smut and weld smoke.

Residue testing is a quantitative method of testing the cleanliness of a surface. Soils are removed by solvent extraction with an organic solvent followed by evaporation of the solvent. Once the solvent has been flashed, the remaining residue from the part is carefully and accurately weighed and expressed in terms of milligrams per square meter of surface area.

Another helpful test of cleanliness is the use of a black light. An oil soluble fluorescent dye can be mixed with an oily soiling material and applied to the test panels. After the panels are cleaned, the remaining soil is visible under ultraviolet or black light. Many common metal working fluids fluoresce under a black light. Black lights are relatively inexpensive. In order for this test to work, it is important to know that the soils being tested will fluoresce under a black light.

Yet another method to test cleanliness is a contact angle water drop test. A drop of water is placed on the test surface; the contact angle is then measured photographically or by a contact angle goniometer. The contact angle varies with the level of cleanliness of the substrate. Although this is an accurate method of determining surface cleanliness, it can only be used under laboratory conditions.

Infra red (IR) spectroscopy can also be used to test cleanliness. A cleaned surface can be stripped with a solvent cleaner. The solvent used for cleaning is then analyzed for any soils remaining that would indicate the part is not clean. Another way of using spectroscopy is to rub a salt onto the surface to pick up any impurities. The salt is then pressed into a pellet. The pellet is analyzed with the spectrophotometer for impurities.

### 1.1.9 SUMMARY

Cleaning is a very critical step in the coating process. Adhesion, appearance, and corrosion resistance are directly related to good cleaning. Proper cleaning requires careful and accurate management of the washer and the cleaning chemical solutions.

Planning and managing a cleaning process begins by recognizing the relationship between the substrate, soil, method of application, and the appropriate chemical solutions and how each impacts the cleaning process.

The four factors of time, temperature, mechanical force, and chemical concentration combine to provide the necessary quality level. These four factors must be measured and maintained routinely for consistent results. Good system management and regular testing of the cleaning results is the first building block of coating success.

## 1.2 CONVERSION COATINGS

A conversion coating is a chemically applied treatment that is used over a clean metal surface to enhance adhesion and corrosion resistance. Iron and zinc phosphate coatings are the most commonly applied conversion coatings. Other conversion coatings include manganese, chromate, zirconium-based products, and vanadium/zirconium-based products. A conversion coating converts the surface of a metal substrate to a uniform, inert surface, which increases paint bonding, minimizes the spread of corrosion under the film if the coating is cut, and improves the overall corrosion resistance of the final product.

Conversion coatings are developed on both ferrous (iron based) and nonferrous surfaces (zinc, aluminum, terne, and manganese). Parts are subjected to an acidic bath in which a chemical conversion forms a complete film on the part surface, changing the chemical and physical nature of the metal surface.

### 1.2.1 IRON PHOSPHATE

Iron phosphate is the most commonly used conversion coating in the general industrial market. An iron phosphate solution produces a thin, bumpy, or amorphous metal phosphate top coating over an iron oxide base. The surface of the material will typically have a gray to blue iridescent or blue-gold iridescent color after application depending on the coating weight and the base metal. A typical iron phosphate consists of phosphate salts, accelerators/oxidizers, and an optional surfactant package.

The acid salt content, type and amount of accelerator, and the type and amount of acid etchants are adjusted to produce different formulas. Iron phosphate coating formulations commonly contain oxidizers and/or accelerators to generate reactivity on the metal surface. Oxidizers, such as nitrite or chlorate, act to initiate attack on ferrous parts, providing the iron for the iron phosphate coating. Accelerators, such as molybdate or vanadate, provide active sites for iron phosphate deposition. The particular oxidizer or accelerator used in a particular product may affect the performance or appearance of the final coating.

In a three-stage iron phosphate washer, the cleaning and coating are combined by incorporation of a surfactant package in the iron phosphate solution. A source of fluoride ions may be added if aluminum is also being processed to increase the etching effect on the oxide surface of the aluminum.

Iron phosphate coatings can be applied by hand wipe, handheld wand, immersion, or spray washer. The most effective and commonly used method is a multistage spray washer. The number and type of process stages is directly dependent on finished part requirements. Spray washers for iron phosphating are built with as few as two stages and as many as eight. The following list shows the typical sequence of stages from two to eight.

- Stage two—clean/coat, rinse
- Stage three—clean/coat, rinse, rinse/seal
- Stage four—clean/coat, rinse, rinse/seal, deionized (DI) water rinse
- Stage five—clean, rinse, phosphate, rinse, rinse/seal
- Stage six—clean, rinse, phosphate, rinse, rinse/seal, DI rinse
- Stage seven—clean, clean, rinse, phosphate, rinse, rinse/seal, DI rinse
- Stage eight—clean, rinse, clean, rinse, phosphate, rinse, rinse/seal, DI rinse

The iron phosphate coating weight, measured in milligrams per square foot ($mg/ft^2$) or grams per square meter ($g/m^2$), varies with phosphate formulas and

**TABLE 1.3**
**Performance Results with Different Spray Systems**

| Number of Stages | Metals Treated | Degree of Cleaning | Coating Weights (mg/ft$^2$) | Coating Adhesion | Corrosion Resistance |
|---|---|---|---|---|---|
| Two | Steel | Light | 25 | Fair | Poor |
| Three | Steel, zinc, aluminum | Moderate | 25 | Good | Fair |
| Four | Steel, zinc, aluminum | Moderate | 25–45 | Good | Fair |
| Five | Steel, zinc, aluminum | Moderate | 25–70 | Good | Good |
| Six | Steel, zinc, aluminum, stainless steel, copper, bronze, magnesium | Good | 25–90 | Very good | Good |

washer arrangements. The quality of paint adhesion and corrosion resistance is affected by the coating weight. Table 1.3 shows typical results of additional steps in the iron phosphate spray washer.

### 1.2.2 COATING WEIGHT

Phosphate coating weight is measured with test panels that have been run through the washer with all of the process variables under control. After a clean, fresh panel is run through the washer, it is removed, dried, and tested by weighing the panel, removing the coating, and weighing the panel a second time as described next. Clean cotton or surgical gloves are worn to avoid contamination of the sample with skin oils.

- Determine the area of the panel in square feet (width × length)
- Weigh the panel, correct to three decimal places (0.000) and record the first weight
- Immerse the panel in 10% $CrO^3$ in water by weight at 160°F for 10 min
- Rinse with tap water or DI water, if it is available and dry
- Weigh the part again, correct to three decimal places, and record the second weight

Then, complete the formula:

$$\frac{\text{1st wt. in grams} - \text{2nd wt. in grams} \times 1000}{\text{Area in square foot}} = \text{mg/ft}^2$$

### 1.2.3 IRON PHOSPHATE CONTROLS

In addition to the number of process stages, the factors that will affect the weight of an iron phosphate coating are time, temperature, concentration, acid consumed (pH), the condition of the substrate, and the spray pressure.

The contact time must be long enough to allow the chemistry to form a uniform coating on the surface. Longer times will generally allow the solution to build a denser and heavier coating. Too much time can cause a more powdery and less durable coating.

#### 1.2.3.1 Temperature

Manufacturers recommend a proper operating temperature for a given phosphate solution. Solution temperature affects coating weight and density. Soils become more reactive in a heated solution and the chemicals become more aggressive. The temperature should be within the manufacturers recommended range (typically 120–140°F). Tests should be run to determine the optimum temperature for good coating weight with a given system.

#### 1.2.3.2 Chemical Concentration

The chemical concentration can be adjusted to achieve the correct coating weight at a particular time and temperature. A higher concentration of chemical will provide more total acid, more accelerators, and typically more coating weight.

#### 1.2.3.3 Acid Consumed

The last factor that affects iron phosphate performance is acid consumed (pH). A higher pH will provide less acid and less coating, while a lower pH will provide better cleaning and more acid. More acid will provide more pickling and heavier coatings. Excessive acid can cause too much pickling and the dissolve the phosphate coating.

The following graphs show the relationship of each of these control factors to the phosphate coating weight.

### 1.2.4 ZINC PHOSPHATE

Zinc phosphate is a nonmetallic crystalline coating that chemically adheres to the steel. A zinc phosphate coating will provide improved paint adhesion properties, better coating in recessed areas, and better corrosion resistance than can typically be obtained with iron phosphate. A typical zinc phosphate consists of

- Phosphoric salts
- Accelerators
- Zinc salts
- No surfactant package

Unlike the iron phosphate, a zinc phosphate solution cannot clean and coat simultaneously in a three-stage process. A separate cleaning stage is required and a prezinc conditioning stage is usually required.

### 1.2.5 ACTIVATING (PRIOR TO ZINC PHOSPHATE)

An activator is used prior to the application of a zinc phosphate. Activators/conditioners are mild alkaline suspensions of specialized active titanium salts that adhere to steel, zinc, and aluminum surfaces. The conditioner will set up a network of uniform acceptor sites for zinc crystals to deposit to increase the number of zinc phosphate crystals and decrease the size of the crystals. The small densely formed coating provides the best possible adhesion and corrosion resistance. A large crystal structure is more porous, has poorer corrosion resistance, and requires more paint to achieve a complete film.

The control measures for zinc phosphate coatings are the same as iron phosphate (concentration, contact time, temperature, and pH). The bath life is also a factor in solution performance.

Accelerators such as nitrate, chlorate, or nitrite are added to control the rate of coating formation. The proportion of these various ingredients affects the coating weight and phosphate crystal size. Fluorides are added if aluminum must be processed.

The reactions at the surface of the part during zinc phosphating are

1. Pickling attack on the metal and oxidation of hydrogen to water
2. Increase of the pH at the interface of the metal and the phosphate solution
3. Oversaturation of the film with coat forming substances
4. Nucleation on the metal
5. Growth of phosphate coating
6. Oxidation and precipitation of iron as sludge

The composition of the bath, the temperature, exposure time, and the previous cleaning process will affect the phosphate composition and crystalline phase.

Zinc and polycrystalline phosphate solutions do require more careful attention than iron phosphate processes to produce consistent high-quality results. Automatic feed pumps can be used for additions of zinc phosphate and nitrite accelerator to the bath to maintain the proper concentration and ensure consistent good quality and minimum chemical consumption. An improper concentration of these materials may result from bulk additions and produce coatings that are soft or too heavy, and it may also create excessive sludge. If the materials are allowed to run too low, the coating will be coarse and spotty, resulting in poor adhesion and corrosion resistance.

Zinc phosphate is the preferred conversion coating used by the automobile industry because of the need for superior corrosion resistance. The coating is firmly attached to the metal by ionic bonding, the porous crystalline structure provides an extended surface for paint bonding, and if the paint surface is scratched, the inorganic coating helps stop the spread of corrosion.

A zinc phosphate solution will continually produce sludge through oxidation of soluble iron to an insoluble state that precipitates. A sludge removal system must be

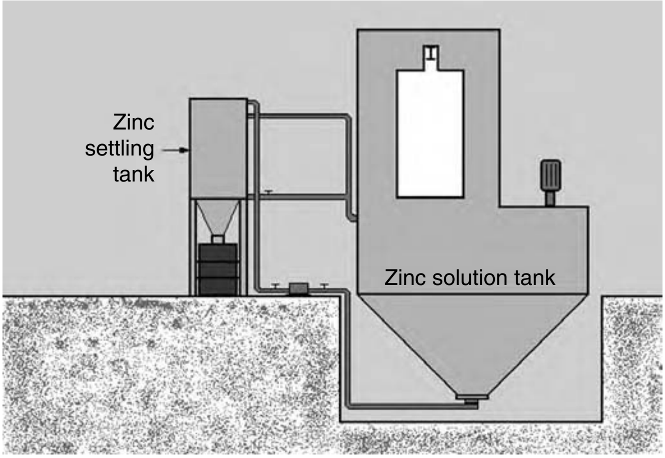


**FIGURE 1.3** Zinc phosphate tank.

used to provide constant removal of this sludge. A simple sludge removal system is shown in Figure 1.3.

The rinse stage following the phosphate should be ambient tap water. Phosphate salts are more soluble in cold water. The overflow volume should be sufficient to keep the rinse clean and reasonably cool.

### 1.2.6 COMPARISON OF IRON PHOSPHATE TO ZINC PHOSPHATE

From an environmental standpoint, iron phosphate is the clear winner. In some municipalities, an iron phosphate solution can be neutralized and released to drain. Some coaters have waste treatment for iron phosphate or they have it hauled away for treatment by a licensed waste hauler. Zinc is listed by the Environmental Protection Agency (EPA) in the Resource Recovery and Reclamation Act (RCRA) as a hazardous substance that is subject to waste regulations. It must be treated prior to discharge and the sludge must be waste hauled.

In terms of performance, zinc phosphate with a chrome sealer will typically provide far superior corrosion resistance.

Table 1.4 compares the two phosphate processes in more detail.

When deciding between zinc and iron phosphate, the end use of the product is the most important factor. For indoor use in noncorrosive environments, iron will work well, and it has several economic and environmental advantages. Zinc will provide the undercoat protection needed for the more demanding product used outdoors or in highly corrosive environments.

The quality of the cleaner and the finish coat is also an important part of corrosion resistance. The ultimate life of a coating is related to the conversion coating combined with the paint applied over the surface. A very good job of cleaning and high-quality topcoat may allow the use of a less resistant conversion coating.

### TABLE 1.4
### Comparison of Zinc and Iron Phosphate

| | **Iron Phosphate** | **Zinc Phosphate** |
|---|---|---|
| Average coating weights | 15–90 (mg/ft$^2$) | 50–100 (mg/ft$^2$) |
| Surface structure | Amorphous (less paint needed to cover) | Crystalline (more paint needed to cover) |
| Paint adhesion | Very good | Excellent |
| Salt spray resistance | 200–500 h | 600–100 h |
| Cost | One product typically<br>Average $4.00–8.00 per gallon | 3–4 components<br>1. Zinc phosphate—$8.00/gal<br>2. Accelerator—$8.00/gal<br>3. Activator—$7.00/lb<br>4. pH adjust—$3–5.00/gal |
| Sludge formation | Moderate | Heavy |
| Bath life | Very good | Very good |
| Control of bath | Very easy<br>1–2 tests | Difficult<br>3–4 test, control of zinc bath and conditioner |
| Equipment | Mild steel or stainless steel | Stainless steel or similar noncorrosive construction; sludge removal equipment needed; more washer stages |
| Maintenance | Minimal | Higher (sludge removal) |

## 1.3 RINSING

Rinsing is a critical part of successful pretreatment. Proper rinsing between process stages is essential to successful pretreatment. Poor rinsing will leave residues on the part surface that will interfere with subsequent steps in the process. Final rinsing is also critical. Soils or unreacted salts left on the surface can cause adhesion failure or premature corrosion.

If the alkaline cleaner is not thoroughly rinsed off, it will carry over into the acidic phosphate solution, where it will increase chemical usage and decrease performance. If the final rinse overflow or dump cycle are inadequately maintained, then, salts will accumulate in the rinse. These salts will dry on the substrate and interfere with coating adhesion and corrosion resistance. Water impurities or salts can ruin all of the hard work of the coating process and shorten the useful life of the product. Water salts can consume pretreatment chemicals such as fluoride, phosphate, and silicate to produce scale. Organic materials such as rust preventatives, metal working fluids, and surfactants can produce scale, sludge, and create foam. The insoluble inorganic and organic matter can produce surface defects and plug risers and nozzles in the chemical as well as the rinse stage. Maintaining clean rinse water will help avoid these problems and will reduce maintenance requirements to the washer nozzles and plumbing.

The rinse following the cleaner should have an aggressive spray pressure to assure removal of all residual alkaline cleaner and soils. The overflow rate is adjusted to keep a slight amount of alkalinity in the water, reducing precipitation, helping to avoid flash rust, and ensuring more complete rinsing of soaps, fats, oils, grease, and surfactants. Some carry-over heat will warm the rinse water and improve solubility.

The rinse following the phosphate stage is operated at a lower spray pressure to avoid disturbance of the freshly deposited conversion coating. A degree of acidity aids in the removal of nonreacted metal phosphate salts. The postphosphate rinse is operated cooler than the cleaner rinse to stop the reaction between the solution and the metal. Lower temperature and spray pressure rinsing will reduce streaking or striping. If the postphosphate rinse is operated too hot and is too contaminated, then, the pretreatment quality will be compromised. Phosphate removal and flash rusting can occur under these conditions.

Both rinses should be overflowed at a rate that will keep them clean enough to ensure the integrity of the steps in the pretreatment process. Overflow rates are typically maintained between 3 and 10 gal/min. Rinse tanks should be dumped frequently to reduce the accumulation of contaminants and to avoid bioactivity. Overflow rates vary due to the amount of drag out or carry over from the previous stage. Drag out varies based on part configuration, rack design, and drainage time. Excessive chemical carry over can be minimized by proper rack design, part orientation, and drainage time.

Rinse water hardness in the final rinse should be maintained below 300 parts per million (ppm). Hardness or water solids can be measured with a total dissolved solids (TDS) meter. A conductivity meter can also be used to indicate the amount of solids in a rinse solution. Conductivity and TDS values are used as a reference point for solution control purposes. Fresh water can be added directly into the rinse tank or through a riser located after the recirculating rinse stage. The added dilution ratio of the residual recirculating rinse water combined with the flushing action of the spray reduces the chemical residues to a point near zero. The fresh water riser increases the efficiency of the rinse by a factor of 400+, using the same quantity of fresh water.

### 1.3.1 RINSE AND RINSE SEAL

Water rinsing only removes the active chemicals (acid) left on the metal surface. Nonreacted chemicals left on the surface can cause corrosive conditions under the applied coating. The rinse seal neutralizes any residual water-soluble salts to prevent humidity blistering and further removes phosphate solution residue. The final seal rinse stabilizes the surface pH to prevent alkaline undercutting, typically leaves the surface slightly acidic, and sometimes can seal voids in the phosphate coating. A final rinse pH of 4.0–5.5 eliminates carbonates in the water and prevents the precipitation of metal hydroxides.

Historically, final rinses were dilute chromic acid solutions in water. Environmental legislation has driven a demand for nonchrome rinses that can provide the same corrosion protection provided by rinses that contain chromic acid.

Some nonchrome rinses perform quite well. For example, some dry-in-place nonchrome rinses can dramatically improve corrosion resistance on aluminum. Chromium containing rinses still provide the best results over a broad variety of parts and operating conditions.

In some cases, a nonchrome rinse is not needed and provides marginal benefit. DI or reverse osmosis (RO) water may provide a great final rinse treatment.

### 1.3.2 Reverse Osmosis (RO) or Deionized (DI) Water Rinse

Final rinsing may or may not include a proprietary chrome or nonchrome product. Some final rinse compounds require a DI rinse to remove any accumulation of the seal rinse or phosphate that might impair the quality of the applied coating. Some nonchrome seal rinses should not be followed by a pure water rinse.

Phosphate residue left on the metal surface can cause nonuniform paint deposition and adhesion problems. DI rinsing will eliminate mineral spotting and corrosive salts that can cause humidity blisters and organic particulate that can cause surface defects.

A DI rinse often includes a recirculated spray zone followed by a fresh DI halo in the exit vestibule of a spray application. The DI water in the recirculation tank should not exceed 50 $\mu$mho conductivity. The fresh DI make-up water supplied by the final halo should not exceed 10 $\mu$mho.

RO purifies water by using pressure to force it through a membrane that will not pass dissolved salts. Because an RO system is a pressure-driven filtration method, it may not take out certain ions and it may be slightly less effective than deionization. However, RO water can be used for final rinsing in the same manner as DI water.

DI water systems may cost less than RO systems in some cases for a particular flow rate. Some of the cost consideration is related to the features of the particular system, like holding tanks, types of regeneration (manual, semiautomatic, or automatic), monitoring equipment, and gauges. It is difficult to compare the equipment cost without an expert to relate the features and benefits. In general, the DI system will not be much less expensive than the RO system unless it is lacking certain important features.

One thing that is consistent is the cost per gallon. RO water is less expensive by the gallon. The list of features in Table 1.5 gives some idea of how the two systems compare. A comprehensive comparison of the features is recommended before

**TABLE 1.5**
**Features of Reverse Osmosis Versus Deionized Water**

| Deionized water system—ion-exchange technology for the removal of dissolved minerals, salts, and gases | Reverse osmosis system—membrane separation technology for the removal of all categories of impurities except gases |
|---|---|
| Can be fouled by precipitated material or organics | Membranes may be fouled by excesses of submicron particulate or some organics |
| May have trouble with excessive bacteria | May be scaled by mineral deposits |
| Effluent must be neutralized | Hardness needs to be inhibited by softening or chemical addition |
| $CO_2$ gas increases cost of operation | Feed water temperature will affect flow rate |
| Requires storage and handling of strong acids and bases for regeneration chemicals | May need to add flocculent periodically |
| Time required for regeneration | Sometimes higher equipment cost |
| Higher operating cost | |
| System may cost less than RO | Do not require acids or caustics |
| | No regeneration required |
| | Lower cost of operation |

making a decision to buy a DI system. They are harder to own and operate and the water is more expensive per gallon.

### Cost Assumptions

| | |
|---|---|
| TDS | 340 ppm |
| Hardness | 18 grains /gal |
| Hours of operation | 20/d |
| Flow rate | 30 GPM |
| Electricity | $0.05/kWh |
| Water | $1.60/1000 gal |
| Municipal sewer | $1.43/1000 gal |
| Labor | 50.00/h |
| Operating days per year | 365 d |
| 30% HCl (55-gal drum cost) | $1.00/gal |
| 50% NaCH (55-gal drum cost) | $1.31/gal |
| Commercial antiscalant | $13.27/gal |
| Commercial flocculent | $26.00/gal |
| NaCl (softener salt) | $0.07/lb |
| Activated carbon media | $\$69.00/\text{ft}^3$ |
| Cation resin | $\$95.00/\text{ft}^3$ |
| Anion resin | $\$232.00/\text{ft}^3$ |
| 8″ Spiral TFC RO membranes | $1000.00 each |
| 10″ poly wound RO cartridges | $7.00 each |

## TABLE 1.6
## Cost Comparison of DI and RO Water

| Auto DI System | | | Reverse Osmosis System | | |
|---|---|---|---|---|---|
| | Cost/1000 gal | Cost/year | | Cost/1000 gal | Cost/year |
| Acid (HCl) | 2.93 | 30,761.43 | Heat | 1.43 | 15, 065.40 |
| Caustic (NaOH) | 1.73 | 18,119.37 | Electric booster pump | 0.10 | 10, 052.92 |
| Activated carbon | 0.02 | 200.00 | Activated carbon | 0.02 | 200.00 |
| Cation resin replacement | 0.05 | 500.00 | Prefilter replacement | 0.06 | 672.00 |
| Anion resin replacement | 0.22 | 2,350.00 | Softener salt | 1.19 | 12, 584.37 |
| Electric recirculation pump | 0.10 | 1,074.56 | Membrane replacement | 0.12 | 1, 200.00 |
| Regen. water and sewer | 0.55 | 5,811.48 | Electric RO pump | 0.28 | 2, 909.37 |
| Labor | 3.62 | 38,084.21 | Electric dist. pump | 0.10 | 10, 052.92 |
| | | | Water and sewer | 1.30 | 13, 688.50 |
| | | | Labor | 0.40 | 4, 2451.67 |
| Total operating cost | $9.21 | 96,846.05 | Total operating cost | $5.00 | 52, 667.14 |

## 1.4 TYPICAL SPRAY WASHER SYSTEMS

The three-stage iron phosphate washer is commonly used for applications that do not process heavily soiled parts or parts with lower quality specifications. The three-stage iron phosphate process combines the cleaning and phosphating steps in a single stage, reducing pretreatment costs and space requirements.

Cleaner solutions in more complex washer arrangements are usually alkaline while the phosphate solutions are acidic. The three-stage washer uses an acidic solution with a detergent package.

In a three-stage system, the cleaning and phosphating processes are compromised and the result is adequate but not good enough for higher quality standards. Much better cleaning and phosphating is accomplished when these processes are separate with rinses in between. Separating the cleaning and phosphating allows the processes to be adjusted for maximum benefit of each process function. The result is much more complete cleaning and a more uniform and complete phosphate coating.

Rinsing between chemical stages prevents excess contamination and the resultant higher cost of added chemical is an addition to maintain high quality. Some processes incorporate two rinses between chemical stages to reduce cross contamination. Adding the extra rinse tank will turn a three-stage washer into a four-stage washer and a five-stage into a six-stage washer, and so forth. Some typical process sequences for spray washers are shown below.

### 1.4.1 Stages of Pretreatment

*Three-Stage Iron Phosphate*

Stage 1—Clean/phosphate: 90 s at 160°F (71°C)
Stage 2—Rinse: 30 s at ambient
Stage 3—Rinse/seal: 30 s at 120°F (49°C)

*Five-Stage Iron Phosphate*

Stage 1—Alkaline cleaner: 90 s at 160°F (71°C)
Stage 2—Rinse: 60 s at ambient
Stage 3—Iron phosphate: 60 s at 140°F (60°C)
Stage 4—Rinse: 30 s at ambient
Stage 5—Rinse/seal: 30 s at 120°F (49°C)

*Seven-Stage Zinc Phosphate*

Stage 1—Alkaline cleaner: 90 s at 160°F (71°C)
Stage 2—Rinse: 30 s at 110–120°F (43–49°C)
Stage 3—Activating rinse: 30 s at ambient
Stage 4—Zinc phosphate: 60 s at 140°F (60°C)
Stage 5—Rinse: 30 s at ambient

Stage 6—Chromic seal: 30 s at 120°F (49°C)
Stage 7—DI rinse: 30 s at ambient (Recirculated)

Fresh DI halo in the exit vestibule.

*Eight Stage Iron Phosphating—Dip Spray*

Stage 1—Immersion clean: 2 min at 150°F (66°C)
Stage 2—Spray clean: 1 min at 100–150°F (38–66°C)
Stage 3—Spray rinse: 1.5 min at 100–150°F (38–66°C)
Stage 4—Immersion rinse: 0.5 min at 140°F (60°C)
Stage 5—Immersion phosphate: 2 min at 140°F (60°C)
Stage 6—Immersion rinse: 0.5 min at 140°F (60°C)
Stage 7—Spray chromic rinse: 1.5 min at 100–150°F (38–66°C)
Stage 8—DI-water rinse: 0.5 min at ambient

*Five Stage for Plastics*

Stage 1—Preclean: 20 s at ambient
Stage 2—Cleaner: 60 s at 130–140°F (54–60°C)
Stage 3—Cold water rinse: 30 s at 70–110°F (21–43°C)
Stage 4—Rinse with rinse aids: 30 s at ambient
Stage 5—DI water rinse: 20 s at ambient

Many variations may be used depending on the mixture of substrates, types of soils, and quality goals of a particular coater.

Cleaning and surface conversion applications utilize immersion or spray techniques. Each method has advantages and limitations and some pretreatment systems use a combination of immersion and spray stages to provide complete cleaning of the part. Car bodies usually require immersion stages for complete wetting and spray stages for good rinsing and effective scrubbing action on the exterior.

Immersion systems have the advantage of reaching recesses and other areas of the parts that might not be accessible by spray. Pockets of trapped air, however, can cause problems for immersion systems. Entrapped air can prevent the entry of cleaning solution into recesses and in extreme cases, make it impossible to submerge a part.

Consistent temperature control and heat transfer is generally better and faster in immersion applications. Heat is lost more quickly when a solution is sprayed through cooler air. Heat transfer is better due to consistent solution contact temperature.

The disadvantages of an immersion system include soil redeposition and solution impact. If contaminants are allowed to float on the top of the immersion tank, then soil redeposition may occur. Agitation of immersion solution will help prevent soil redeposition. Spray halos have also been employed to flush away any redeposited soil. If the solution is not agitated, it will not be as effective at removal of softened soils. Eductor systems can help keep the solution in motion and improve cleaning, as well as reduce soil redeposition.

Spray systems use pressure to provide impingement energy to dislodge dirt and remove loosened soils. Sprays can often be directed into recesses. Spray systems may hold less water in cupped areas of the part.

Spray nozzles must be properly maintained to perform correctly. A routine maintenance procedure should be put in place to examine the nozzle orifices for obstructing debris, nozzle alignment for spray angle, and the nozzle body for proper seating. Routine nozzle maintenance will avoid clogging or other problems that lead to a poor spray pattern and reduced process effectiveness.

## 1.5 SUBSTRATES

Substrate is a reference to the material that the product is made of. The type of substrate, along with the desired performance characteristics of the finished part to be coated, will influence the selection of pretreatment chemicals and the system used to clean and treat the product. Different materials will have different soils and surface conditions that require different chemistry and process sequences to properly prepare them for paint application. It is very important to understand different substrate surfaces and the types of treatment that work best with different materials.

### 1.5.1 METAL SUBSTRATES

Metal surfaces are highly reactive and the oxide layer that forms on the surface can interfere with adhesion, appearance, and performance. Rust inhibitors, such as mill oil and metal working products containing rust inhibitors, are used to temporarily prevent rust, but the metal will eventually begin to oxidize. The rust inhibitors and metal working fluids age and they may react with the substrate to form compounds that interfere with the appearance and quality of the finished substrate. Therefore, the rust inhibitors must be removed and the surface must be free of oxides before the paint can be applied.

The base metal itself is also a factor that must be considered in selection and application of a particular treatment method. The components that make up the metal can cause contamination on the surface that will interfere with good coating adhesion and corrosion resistance. For example, higher carbon steel alloys will create more smut than lower carbon alloys. Mill scale and other substances that are difficult to remove chemically may interfere with paint adhesion. Other examples of surface conditions that create metal treatment issues are silicon in aluminum alloys and chromate passivation on aluminum or galvanized steel. The substrate and the surface of the part must be thoroughly understood to make a reliable system for pretreatment.

The most common metal substrate materials that gets painted are cold-rolled steel (CRS), HRS, aluminum (cast and extruded), galvanized steel, galvaneal, and cast zinc. Copper, brass, bronze, and stainless steel are sometimes painted but not as often as other metals.

Metals have certain natural properties as well as modified physical properties that occur through alloying and heat-treating. Alloying occurs by mixing two or more metals or nonmetals to achieve a certain desired property in the finished product.

Different alloys are available in various forms such as castings, wire, or sheet products. Aluminum is alloyed with silicon, copper, magnesium, and other materials to provide products with slightly different properties such as hardness.

### 1.5.1.1 Steel

Steel is the most common substrate material used in manufacturing. Steel, available in a variety of alloys and forms, is made from iron and a small controlling amount of carbon (~2%) with small amounts of various alloying additives. Initial refining of steel produces thicker and rougher grades of structural steel and plate. Further refining of iron reduces the carbon and other impurity levels. Steel is sometimes classified by carbon content.

*Low Carbon, 0.25%*

- Machining steel, mild steel (MS)
- Easy to cut and form: typical uses—nails, bolts, automobile bodies, and metal furniture

*Medium Carbon, 0.25–0.55%*

- Greater hardness and strength
- More difficult to form: typical uses—axles and drive shafts

*High Carbon, 0.55–2.00%*

- Greatest hardness and strength
- Most difficult to form: typical uses—cutting tools, files, and hammers

A four-digit system is used to classify different types of steel.

Primary four-digit numbers

- First digit, basic kind of steel
- Second digit, general class of steel
- Third and fourth digits, allowable range of carbon (in hundredths of %)
  Example: 1010 carbon steel has 0.10% carbon content
- Fifth digit used where carbon is greater than 1%

Steel stock is available in plate (0.23″ minimum thickness), sheet, or coil (0.23″ maximum thickness), bar stock, rod stock, tubing, and structural forms.

Steel is available in different forms that can affect the pretreatment selection.

- *HRS*—rolled (flattened) while red hot. A blue/black coating consisting of iron oxide forms on the surface as the steel cools. Used in applications requiring substantial structural strength.

- *CRS*—rolled to finished size while at ambient temperature. No oxides form during processing. Much better aesthetics, superior surface, and mechanical properties. Many common products are produced from CRS.
- *Hot rolled, pickled, and oiled (HRPO)*—HRS that has had the oxides removed through acid pickling. The steel is rinsed and then oiled to inhibit corrosion. Used in applications that require heavier gauges of steel and a better surface condition than HRS.
- *Cast iron*—usually refers to gray cast iron, but can mean any of a group of iron-based alloys containing more than 2% carbon (alloys with less carbon are carbon steel by definition). Used to cast heavy parts in machinery and other applications.
- *Stainless steel*—contains at least 11% chromium by weight—some alloys also contain nickel. Used for appearance and corrosion resistance.
- *Hot-dipped galvanized steel*—steel that is coated with a thin layer of zinc by passing the steel through a molten bath of zinc at a temperature of around 460°C to form zinc oxide to protect the steel below from the corrosion. Galvanized steel is widely used in applications where rust resistance is needed.
- *Electro-galvanized steel*—zinc coatings applied to steel electrolytically in zinc ion solutions can provide the same corrosion protection as hot-dipped zinc coatings, but they are smoother and lack some of the impurities that occur in the hot-dip process.

Differences in steel composition can affect the quality of the finished product by affecting the performance of the organic coating. Iron phosphate provides modest performance characteristics and corrosion resistance over steel. Zinc phosphate is used for applications that require more severe performance properties.

#### *1.5.1.1.1 Hot-Rolled Steel*

HRS represents the first reduction in the processing of the steel slab in heavier gauges, 0.1–0.2 in. in thickness or higher. The surface profile is generally rough and porous with a blue/black oxide mill scale covering. Most HRS is used for structural steel components, building trusses, heavy bar stock, and other interior applications.

HRS will have mill scale, carbon smut, and possibly rust, in addition to the soils that have collected during manufacturing. To ensure good quality of the coating, the mill scale and rust must be removed by abrasion, such as a blasting operation. A chemical process may be used after blasting to provide better corrosion resistance.

The inorganic contaminants can also be removed by acid pickling solutions, but there is some risk of flash rusting. Strong acid solutions may also be a health and safety issue and they are sometimes hard to maintain. Pickling solutions will also accumulate iron sludge that must be filtered or removed.

#### *1.5.1.1.2 Cold-Rolled Steel*

CRS is characteristically thinner and has a more uniform surface profile than HRS. This is achieved by further processing of the HRS through a cold roll mill and a tempering process. The difference in surface profile and reduction in porosity is one of the reasons why CRS is used for exterior products. Typically, a series of chemical processing tanks will be sufficient pretreatment for CRS. Oils and other organic soils can be removed with a cleaner, and conversion coatings can be added for enhanced performance. Surface rust or weld burn may need mechanical cleaning to ensure good coating adhesion and corrosion resistance.

#### *1.5.1.1.3 Hot-Rolled Pickled and Oiled (HRPO)*

HRPO steel is hot-rolled coil or sheet steel that has been descaled of oxide film by either a chemical method, mechanical method, or a combination of both and oiled to help retard corrosion during storage. HRPO is available in various gauges, widths, and cut lengths or coil. HRPO is often used for products that need a better surface for appearance. Most chemical cleaning processes are effective for preparation prior to painting. HRPO will develop less scale on the edges during laser cutting than HRS.

#### *1.5.1.1.4 Cast Iron*

There are many variations in the composition of cast iron products to impart different properties for strength, hardness, softness, and abrasion resistance. The high carbon content of cast iron should be considered when cleaning prior to phosphating and painting.

Cast iron can be cleaned with an alkaline cleaner for the removal of dust, oil, and other organics. The high carbon content may cause smut if the alkaline cleaner is too strong. Acid cleaners or pickling solutions can be used to remove rust and other inorganic substances. Iron phosphate is the most common conversion coating used on cast iron.

#### *1.5.1.1.5 Galvanized Steel*

Hot dipped galvanizing is an extension of the HRS/CRS process. The CRS is immersed in a molten zinc bath and withdrawn to provide a smooth coating that frequently has a crystalline spangled appearance. Some coatings may not adhere to a galvanized surface. A wash primer is one of the few products that can be used on galvanized steel as a tie coat or adhesion promoter between the substrate and the subsequent application of a primer and topcoat.

Alkaline cleaners work well on hot dipped galvanized surfaces, and most multimetal cleaner/coater products will provide sufficient etching for good adhesion.

#### *1.5.1.1.6 Electro-Galvanized*

In an electro-galvanizing process, the zinc coating is applied using an electrical charge to attract the zinc to the steel surface. It produces a more uniform surface without some of the variations in appearance that are common with hot-dipped galvanized steel. The surface resembles sharkskin with many very small pores. It is highly reactive, so oil is applied to prevent white rust.

The oil needs to be removed, but the reactivity limits the possible chemicals that can be used. A hot neutral cleaner followed by a mild etch with fluoride will provide a good surface for paint bonding.

Galvanized material may also have trapped air or gasses that will expand and release in the cure oven, causing small pinholes in the surface. Some testing of cure oven cycles is recommended before production is started.

Galvanized steel sometimes goes through a "passivation" process, which makes the surface of the steel almost inert to chemical attack. This type of galvanized steel is often used with no coating applied over it in applications such as highway guardrails, barn roofs, or fencing. This surface is almost impossible to coat without special preparation or coatings.

#### *1.5.1.1.7 Galvanneal*

Galvanneal is prepared by heat-treating hot dipped galvanized steel so that the alloy layer grows to the surface. It provides superior corrosion resistance compared to hot dipped galvanized, and it can be treated with similar processes to electro-galvanized.

### 1.5.1.2 Aluminum

Aluminum is produced from a mineral called bauxite. It is used for its low density, corrosion resistance, and electric and thermal conductive properties. It conducts heat five times better than steel. Aluminum forms a natural aluminum oxide layer that protects from air and elements.

Aluminum products are available in a variety of alloys possessing different physical and chemical properties. Aluminum may be cast, extruded, forged, or rolled structural forms. Aluminum alloys need to be cleaned and etched so that the organic coating has a porous surface to adhere to. Coating lines that process both steel and aluminum typically use an etching additive, such as ammonium fluoride, to produce a surface conversion on aluminum.

Wrought aluminum is available in several grades, which are identified by a four-digit numbering system.

- First digit represents the main alloying agent
- Second digit represents modification of alloy's impurity limits
- Last two digits identify particular alloy or indicate purity of the aluminum
- In addition to the four-digit alloy number, a letter or letter/number indicate the temper

Treating aluminum for outdoor products requires a more robust chemical process than simple etching with fluoride in a multimetal treatment chemistry. Traditional treatments usually include chrome to prevent oxidation. Dry-in-place nonchrome seal rinses can also provide the necessary treatment to prevent rapid oxidation and loss of adhesion. Without a suitable chemical treatment the coating is vulnerable to moisture penetration that can lead to rapid coating failure.

## 1.5.2 PLASTIC SUBSTRATES

Adhesion may be a problem on some plastics, due to nonpolar materials such as polyethylene and polypropylene or release agents used in the molding process.

Some plastics, such as polyamide, polycarbonate, and polyester, are easier to coat; however, they are also more expensive.

Types of soils that may be present on plastics include internal mold releases such as fatty acid salts, oils, and polymers; external mold releases such as waxes, fatty acid salts, and polyvinyl alcohols; shop dirt, such as handling oils, skin oils, lubricant from equipment, dust, and smoke tar; and fabricating soils such as plastic grind and sanding dust.

In some cases, plastic substrates can be painted without cleaning. However, steps must be taken to ensure that no surface contamination develops between fabrication and finishing. Because plastic builds a static charge that will attract dirt, parts are usually destaticized prior to painting. Some plastics must be primed, treated with a mixture containing chromic and sulfuric acid, plasma treated, or flame treated to promote adhesion between the substrate and the coating.

In some cases, plastics are hand wiped with solvent prior to the coating application process. Solvent wiping is not consistent and it may not be effective. The use of solvent is not desirable from an environmental compliance standpoint. The process is also less desirable as it is labor intensive.

Aqueous cleaning with a cleaner and a DI rinse or series of rinses, followed by DI air is usually the best way to clean most plastics.

### 1.5.3 Wood Substrates

Strictly speaking, the application of coatings on wood does not require pretreatment. Like all other substrates, wood must be free of surface defects and contamination.

The wood substrate may have surface blemishes that are part of the material or contaminants that got onto the surface during machining operations. These defects should be removed before the first primer coat is put on.

Sanding between coats will improve the appearance. Sanding between coats should be done with a fine grain and a light touch. Over-sanding can remove too much pigment and cause a visual defect after the topcoat is applied. The goal is to remove the raised grain from the wood so the surface is smoother before applying the next coat.

It is also important to remember that wood is an organic substance that has its own color variance and grain. Not every piece of wood will look identical, even if the same paint is used to coat its surface.

## 1.6 WASHER DESIGN

In higher volume production lines, a spray washer is often used to clean and treat parts prior to coating. An industrial washer uses a series of stages that clean and treat the surface to be coated. The number of stages and types of chemistry used in a washer depends on the quality requirements of the coated product and the substrate material. The desired level of quality for the end product should be used to develop a written standard for performance with values for the specific needs of weathering, corrosion resistance, and other properties needed to meet the established standard.

### 1.6.1 WASHER COMPONENTS

Each stage is an independent spray or immersion process that cleans, rinses, or provides some other treatment to improve the surface for paint adhesion, appearance, or performance. The solution used for treatment is held in a tank. In an immersion stage, the parts are dipped directly into the solution. A circulating pump is used to provide agitation in the tank. In a typical spray stage, the part passes through a tunnel and the solution is sprayed onto the surface through a series of nozzles mounted on vertical risers. Heaters, valves, gauges, and so forth are added for control.

An understanding of the pretreatment system, materials, design, and controls is very important to the finishing system operator.

#### 1.6.1.1 Solution Tanks

The size of the tank that holds the chemical solution for a spray stage is based on the pump volume. The amount of solution held should be three times the GPM of the pump plus enough space for internal heat exchangers.

The length of the spray process zone is determined by multiplying the required process time by the design conveyor line speed. In width, the tank will extend beyond the tunnel from 30″ to 40″ as required for the tank access lids and pump mounting plate. The tanks should be around 42″ in depth to allow for the depth of the pump and enough space to keep the pump impeller well above the tank floor.

Double pump screens should be installed to isolate the pump inlet from gross particulate that could be passed to the pump impeller and cause plugging. A single pocket for two screens should be provided so that a cleaned screen can always be slipped in back of the screen still in place. The pump screens should be removed and cleaned regularly with a high-pressure hose to flush off built up dirt and grease.

#### 1.6.1.2 Drainage Spaces

Sufficient space must be allowed between spray zones to guard against mixing of solutions by over spray or drainage from the work being processed. The drain zone is the distance from the center of the last spray pipe in one group of sprays to the center of the first spray pipe of the next stage.

The length of the drain zone is influenced by time, the part shape and size and conveyor speed. Usually, the drain time will be 30–60 s. Long, horizontally hung, parts can have a big impact on the size of the drain zone. It must be long enough so that a part or rack of parts is never entering a process stage while the tail of the part is still in the previous stage. For example, if the parts to be run are 10′-0″ long and the line speed is 8 ft/min, a 60-s drain zone will not work. A 60-s drain zone would be 8′-0″, allowing the part to extend into two stages at the same time, channeling solution directly from one stage into another and producing an unacceptable amount of “cross contamination.” However, when the drain zone is extended beyond 60 s, misting nozzles should be installed in the drain zone to prevent the part from drying, because flash rust may occur. A set of misting nozzles is one riser set (opposing pair) with low volume nozzles that apply a gentle mist of fresh water.

The drain deck between stages is sloped to run solution back into one of the two stages. The drain deck is usually sloped with 70% of its length angled back to the spray zone being exited and 30% of its length angled to the next spray zone (Figure 6.4) However, the apex of the drain zone may have to be in a different position if the parts cup substantial amounts of solution, or if, it will channel solution backward into the preceding stage.

The length of inlet and exit vestibules for the conveyor should be long enough to prevent vapor roll out or excessive dripping from exiting parts. As parts exit the washer, they will still be dripping, so, it is a very good idea to install a drain trench directly under the conveyor for a few feet to prevent water accumulation on the floor.

### 1.6.1.3 Tank and Housing Materials

Although it is well known that MS will rust, many spray washers have been built over the years with MS tanks and tunnels. With MS construction, the cleaner tank and rinse tanks are generally made of 1/4″ thick plate, while zinc phosphate solution tanks are made of at least 3/8″ plate.

In washers constructed of MS, the housing shrouds, conveyor splash guards, drip shields, and vestibule ends, including floors, should be constructed of not less than #10 gauge sheet steel, and floor plates in drain spaces or over open tanks should be of 3/16″ steel plate. The zinc phosphate stage housing is made of heavier plate, because it will rust faster from contact with the corrosive zinc solution.

Stainless steel, either type 316 or type 304, is necessary in some stages, such as a DI water rinse or a zinc phosphate stage. Stainless steel is preferred throughout the machine, because it offers a significant increase in useful life. The stainless steel washer is less likely to contaminate work in progress, it is corrosion resistant, and another important advantage is easier maintenance. The surface remains smooth and does not flake or chip like MS, so screens stay cleaner, solutions stay cleaner and longer and nozzles do not plug as easily. Long-term repairs or replacement of shrouds, profiles, and screens is eliminated. In addition, with some companies there is increasing emphasis on the clean, high-quality appearance provided by stainless steel.

Another alternative material to MS is a composite fiberglass. It offers excellent corrosion resistance and a very cleanable surface and has a good appearance. A composite washer will insulate heated stages and it has the same low-maintenance characteristics as stainless steel.

Another material that can be used for washer construction is polypropylene. It can be welded to provide a leak proof washer and the tunnel will allow some light to penetrate to the interior. The tanks will typically be 3/4″ thick material, providing some insulating capacity. Care must be taken to strengthen the tunnel and tanks with steel to avoid sagging or stress fractures. Polypropylene does not expand and contract very well so leaks are possible over time.

An expanded metal or fiberglass walkway should be provided throughout the length of the washer with suitable structural support. It should be as wide as possible to protect workers from stepping off the edge and to keep parts from falling into the tanks.

The tank drain connections should be large enough for rapid draining. In normal installations, a 2″ overflow gutter drain and a 3″ tank drain from the sump in the tank bottom are provided. The tank drain should be flush mounted or split nipple and fitted with a valve close to the tank. The overflow gutter drain line should be connected to the tank drain line outside the drain valve (Figure 6.5).

#### 1.6.1.4 Zinc Phosphate Tank

Zinc phosphate solutions are corrosive and generate a lot more sludge than an iron phosphate solution. Because of this, it is necessary to use thicker material or stainless steel in the zinc tank, and provisions must be made for sludge removal.

The zinc tank should be designed with a sloped bottom to facilitate the removal of sludge through a permanent suction line to the transfer pump, or through a suction hose and sweeper type hand tool. Heating coils and pumps should be kept well above the tank bottom.

#### 1.6.1.5 Sludge Removal Tank

A sludge settling tank should be located on a structural steel frame convenient to the zinc phosphate solution tank, equipped with piping between the tanks and transfer pump, to be used for periodic transfer of sludged solution from the process tank.

The sludge-settling tank may be square or round and should have a sloped bottom of approximately 30° from the vertical. Tank capacity should be at least one-third of the working volume of the zinc phosphate solution tank.

The settling tank should have a safety overflow line back to the phosphating solution tank and a valved draw-off line located in each cone section and connected into the overflow line for returning the clear solution to the solution tank. The draw-off should be located so that approximately 40 gal of solution can be held in the cone bottom below the draw off line.

The bottom of the cone should be fitted with a 4″ dump valve for sludge removal. The tank should be elevated high enough above the floor level to allow a barrel or suitable container to be placed under the dump valve for sludge removal and also to provide for gravity return of the clear solution to the phosphate solution tank.

#### 1.6.1.6 Access Doors, Ladders, and Lighting

Doors should be built into the housing walls between the spray zones to provide access for maintenance workers or operators to view the spray zones while in operation. The area around the tunnel access door is one of the first places to rust, so the door should be constructed with a vapor tight fit and rugged hinges and latches.

Steel ladders at each access door and at the ends of the housing can be installed for easy access to the inside of the washer. The best design includes a platform and a dock light to illuminate the washer interior (Figure 6.7).

### 1.6.1.7 Pumps

Solution pumps are usually standard side suction, centrifugal type, with open impeller and double bearing shaft supports for direct connection to the drive motor. Pumps with enclosed type impeller are sometimes used, but experience, especially in handling phosphate solutions, indicates that this type of pump requires more maintenance and does not maintain volume delivery and head pressure as well as the open impeller type pump. Barrel mounting pumps are used for dependable performance and ease of maintenance.

Solution pumps for cleaner and all rinses, except a chromic acid rinse, can be all iron construction. Zinc phosphate solution pumps should always be stainless steel construction. Stainless steel pumps add cost to the construction of a washer, but they reduce maintenance and provide substantially longer useful life.

### 1.6.1.8 Nozzles

Glass reinforced polypropylene, clamp-on type nozzles are commonly installed in spray washers. They are relatively easy to clean, change, and adjust when compared to threaded steel nozzles.

In most cleaner and rinse stages a 50–50 flat spray nozzle is best. Nozzle sizes, such as 50–50, refer to the gallons per minute (GPM) of output and fan spray angle at 40 psi. A 50–50 nozzle will spray 5.0 GPM at a 50° spray angle at 40 psi. The output and spray angle will change at lower pressures.

Nozzles are mounted in a staggered pattern to provide good impingement on the entire work surface. Fan spray patterns should be adjusted on a 10° angle from vertical as shown in Figure 1.4.

Nozzles near the end of the process stage should be adjusted in slightly to help prevent carry over into another stage as shown in Figure 1.5.

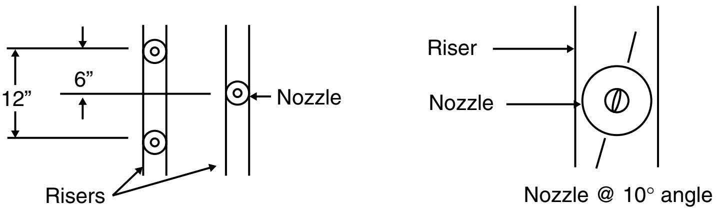


**FIGURE 1.4** Vertical spacing of spray washer nozzles.

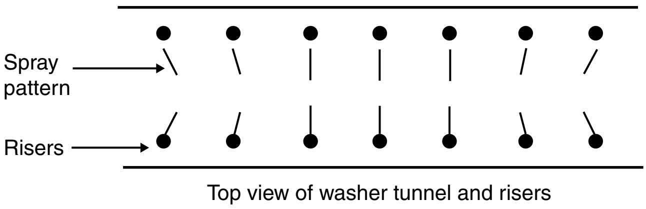


**FIGURE 1.5** Plan view of spray pattern for spray washer nozzles.

In the phosphate section, a hollow-cone-type nozzle should be used. A flooding type nozzle should be used in a final DI halo rinse and most chromic final rinses, where high impact pressure can remove coating.

Typical nozzle volume and pressures

- Cleaner and rinses, 4–5.0 GPM at 15–20 psi
- Iron phosphate, 2.8 GPM at 10–15 psi
- Zinc phosphate, 5.0 GPM at 10 psi
- Misting nozzles (for wetting in drain zones), flooding type, 0.5 GPM at 10 psi

***Note***: It is good practice to connect the last riser in a rinse stage to a fresh water supply and use it as make up water. This gives excellent rinsing and a flow meter and valve attached to the inlet gives very accurate control of the overflow rate.

### 1.6.2 WATER CONSERVATION

Water conservation can save money by reducing water usage and preserving the life of the chemical solutions. Proper use of water can also improve quality and reduce maintenance. Counterflow and filtration methods can be used that will improve performance and reduce costs.

Counterflow of the rinse stages from the last rinse back toward the preceding stages is one popular way of saving water. The proper way to do this is to attach a pipe from the discharge of the final rinse, plumb it to the preceding stage and connect it to a pair of risers with nozzles that have a very low flow rate, 0.3–0.5 GPM. This set of risers will spray the parts as they exit the process stage, providing extra rinsing, and the overflow will drain to the process tank as make up. Fresh water will be introduced to the final rinse to make up for this overflow to the preceding stage. The make-up pipe and the counterflow pipe should be equipped with a flowmeter and manual ball valve to regulate the volume. This counterflow method makes the final rinse the cleanest water and reuses overflowed water. The chemical supplier can suggest the proper stages to overflow and what volume.

Oil skimmers used on the cleaner stages can significantly increase the life of the cleaner bath and improve the performance of the cleaner solution. Belt type oil skimmers are inexpensive, but they do not remove a significant volume of oil per hour. A circulating system that separates the oil and returns the solution back to the tank can remove much higher volumes of oil. Membrane type systems can also be very effective, but they do require more maintenance.

Bag filters can be used on chemical stages to filter solution and keep the volume of solids to a minimum. A floor sweeping pipe and independent circulation pump will make the filter work better by providing a push to the heavier solids along the tank floor. Solids are flushed along the floor of the tank toward an outlet by rows of nozzles or eductors. A circulating pump pulls the solution out, passes it through the filter to remove the solids, and returns it to the tank. This arrangement is more costly than a system that uses the process pump, so, it is more practical for line speeds over 15 ft/min with larger tank volumes.

## 1.7 WASHER MAINTENANCE AND CONTROL

The washer is one of the most critical components in the finishing process. Good chemical and mechanical maintenance is essential for reliable coating performance. A regular maintenance schedule with daily, weekly, monthly, and annual tasks should be used to keep the system working properly.

### 1.7.1 MECHANICAL MAINTENANCE

Regular inspection of the washer is needed to make sure that it is able to perform up to standard. The inspection should be used to determine that the washer plumbing is clean and in good working order.

Nozzles can become worn, plugged, or misaligned so that the chemical performance is reduced. Nozzles should be inspected daily to confirm proper spray patterns. Worn nozzles will not produce a finely atomized spray pattern and should be replaced. Plugged nozzles will not spray at all and should be removed and cleaned by removal of obvious debris and soaking in a descaling solution.

Pump screens should be removed daily and rinsed with high pressure.

Water replenishment systems should be checked daily to make sure that valves are functioning properly. It is important to keep the level sensors clean to make sure that they function correctly.

Thermocouples, temperature gauges, and pressure gauges should be calibrated at least once a year.

Pumps should be greased as recommended by the manufacturer and inspected monthly for vibration, leaks, or overheating.

The inside of the spray risers will develop scale over a period of time and restrict flow of solutions. The inside diameter should be inspected regularly and end caps removed to drain debris. The frequency for inspection and cleaning can be determined by observing the condition of the bottom nozzles; if the bottom nozzles plug frequently, the risers probably have excess scale buildup. Scale buildup will restrict the flow of the process solutions, reducing the volume that will affect the pressure and performance of the sprayed solution.

Internal heat exchangers will build scale on their surfaces that will reduce efficiency. A scale buildup of 1/32″ can reduce heating efficiency by 2%. Lime scale deposits conduct only 3% of the amount of heat as an equivalent thickness and area of steel. The heat exchangers should be inspected monthly and descaled periodically.

Gas fired burners should be serviced twice a year as part of a preventive maintenance contract with a suitable service contractor. The burner inlet filters will provide a minimum of 1 month service in harsh conditions. They should be washed or replaced on a regular basis.

Plate and frame heat exchangers are external to the tank, but they still require cleaning. The cleaner stage should be flushed with a chelated acid during off hours, and the phosphate should be flushed with a chelated caustic. If the plates are not cleaned regularly, they will restrict the flow of solution and the heating efficiency will drop substantially.

Chemical removal of scale buildup will prevent loss of effective performance and efficiency. Actual time to descale will vary dependent on the size of the system but usually can be completed in 4–8 h.

Acid descaling solutions are effective for removing lime scale and rust, but they are not very effective at removing oily soils or product residues. Usually, it will be necessary to thoroughly flush out the system with a hot (140–160°F) alkaline type of material to remove the oils and grease that build up in the washer.

Once the system is degreased, rinsed, and drained, the plumbing should be inspected to see if any parts are in need of repair or adjustment. Heavy deposits should be chipped away and the sludge should be removed from the bottom of the tank by flushing with a hose or shoveling.

Pretesting the descaling material on a small sample will help to determine the correct material and concentration. Usually, lime scale and rust will form carbon dioxide in an acid solution. Some types of scale, such as those formed by iron phosphates or combination cleaner/phosphates, may produce little or no reaction by exposure to acid based descaling solutions. In cases where pretesting an acid solution does not produce satisfactory results, an alkaline solution should be tested.

In general, the descaling product will be opposite in pH to the process solution that is being removed. Descaling should typically be done once every 6 months to 1 year.

Regular service reports should be kept that document the condition of the washer, including the nozzles, operating temperature, pressures, general appearance, conveyor, and washer interior condition, and so forth. Monitoring the washer condition with this report will give the operator the information necessary to schedule the maintenance in advance.

Any existing leaks in the washer will be enlarged when the descaling solution is run through the system.

### *Descaling Procedure*

1. While the solution is hot, remove as much free oil as possible by overflowing or use of an automatic skimmer.
2. Drain the solution from the tank.
3. Flush sludge and solids to drain.
4. Refill the tank with water.
5. Add a high caustic, high chelate alkaline descaler to reach 4–6 oz/gal.
6. Heat and circulate the solution for 1–2 h at the highest possible heat. A low foam detergent may be added at 0.5–1.0 % by volume to help displace oils.
7. Allow the solution to remain static for 20–30 min.
8. Overflow to displace surface oils or use an automatic skimmer to remove oils.

9. Drain the solution from the tank (treat the solution if necessary or drain to a holding tank).
10. Flush sludge to drain.
11. Remove the nozzles.
12. Fill the tank two-thirds full with fresh cold water.
13. Add 10% by volume, inhibited descaling acid (muriatic). To minimize fuming in the plant, use a low volume chemical hand pump with the discharge line immersed below the solution level in the tank.
14. Circulate and heat the solution to 120°F for 1–2 h.
15. Drain the solution from the tank (neutralize the solution prior to discharge).
16. Flush sludge from the tank bottom.
17. Inspect the nozzles, clean by soaking in a descaling solution, repair or replace as necessary, and reinstall them in the washer.
18. Refill the tank with fresh water and heat.
19. Add 0.1–1.0% by volume of proprietary type phosphate. Circulate washer for 5–10 min.
20. Drain the tank and rinse sludge from bottom.
21. Fill the tank to operating level.
22. Charge the tank with the appropriate processing chemical product.

### 1.7.2 CHEMICAL MAINTENANCE

Chemical performance is very dependent on the process control and maintenance of the solutions. The factors that affect the performance of the chemistries are the amount of exposure time, the pressure at which the solution is sprayed, the concentration of the chemical in the solution, the temperature of the solution, and the control of oil and solids in the tank.

To achieve the intended quality that the pretreatment system was designed for, the chemistry of the washer must be carefully monitored, recorded, and maintained. Specific ranges of operation must be established and controlled. The specific variables to be controlled are process time (line speed), temperature, chemical concentration, pH, and TDS.

Titration is the test process used to check the chemical concentration of a solution. Acid base titration is based on the fact that it will take a certain amount of an acid with a known concentration to neutralize a sample of an alkaline cleaner and a certain amount of an alkaline solution to neutralize a sample of an acid solution.

A solution called an indicator is added to the solution sample prior to titrating. The indicator is usually an organic liquid such as phenolphthalein that will cause the sample to change color when it is neutralized.

Frequency of chemical readings depends somewhat on the volume of product being processed. In most cases, the cleaner stages should be checked for temperature and pressure at the start of a shift, middle, and end. The results are recorded and adjustments are made if necessary.

In the rinse stages, the TDS and conductivity should be tested three times a shift. The TDS and pH should not be allowed to rise very much over the initial raw water readings. Adjustment of the overflow volume will help to control the rinse water quality. In addition, tanks should be drained and cleaned on a regular basis as necessary. The tank dump schedule and overflow rate are related. If a comparatively low volume of water is overflowed, say 1.5 GPM, the rinses may need to be dumped as frequently as once a day. If the overflow rate is 5–7 GPM, the rinses can be typically be dumped once a week. In cases where maintenance of the water quality is critical, softened water can be helpful. Automated rinse control based on conductivity is also possible. The key is to maintain good quality rinse water with low TDS and near neutral pH.

### 1.7.2.1 TDS

TDS can be measured with a Myron L Model 532 MI dissolved solids meter, or a Markson Conductivity/TDS pocket tester, measuring how conductive a water sample is in units of micromhos (μMho), or similar device. Pure water, such as distilled water, conducts electricity very poorly and so it will give a dissolved solids or conductivity reading close to 0 μmho. Ionic matter, such as acids, alkalis, water hardness, or salts, will make the water much more conductive and the dissolved solids reading will rise. The more dissolved water in the solution, the more conductive it becomes.

A low level of conductivity is desirable, because the water will perform better for rinsing. To measure the conductivity of a sample solution, make sure that the meter is calibrated.

### 1.7.2.2 Temperature

The temperature of the solution can be determined with a thermometer such as the Tel Tru Model GT 100B thermometer in degrees Fahrenheit. The thermometer must be immersed past the groove on the lower portion of the stem in order to get accurate readings. To convert degrees Fahrenheit to degrees Celsius, use the following formula:

$$\frac{(°\mathrm{F} - 32) \times 5}{9} = °\mathrm{C}$$

### 1.7.2.3 pH Measurement

The chemical symbol pH represents a measurement of the relative acidity or alkalinity of a solution. A pH of 7 is considered neutral, acidic solutions are below 7, and alkaline solutions are above 7. The pH can be measured with a Markson Model 88 pH meter, a pocket-type pH meter, or pH paper. Measurement of the pH provides a numerical value to relative acidity or alkalinity, an important feature in the controlling the performance of a solution.

For a solution to perform as designed, the desired pH must be known and the solution must be controlled. To illustrate the point, consider the manufacturing of jelly. In order to jell the fruit, the mixture must be slightly acidic. At a pH below 2.6, the mixture will not jell; at 2.6, a white precipitate forms and the resultant jelly is unmarketable; at 2.8, there is a separation of water droplets from the mixture; at 3.1, the mixture will produce a jelly with maximum stiffness; a pH of 3.2 will produce medium stiffness, and at a pH of 3.3 the jelly will be thin. Above a pH of 3.5, the mixture will not jell at all.

Within a few tenths of pH unit, the mixture will go from “no jell” to maximum stiffness and back again to no jell. This clearly illustrates the importance of tight control of the pH of a solution.

Acids, from sulfuric acid that can dissolve metal to boric acid that can be used as eyewash, all produce hydrogen ions ($H^+$) in solution. The measure of acidity is the numerical value of the hydrogen ion concentration. Expressed in chemical terms, the numerical values for hydrogen ion concentrations are usually extremely small fractions such as 1/10,000,000. The pH scale was developed to avoid the use of such inconvenient numbers. The pH scale is defined mathematically as the negative logarithm of the hydrogen ion concentration or the power to which 10 must be raised to equal the hydrogen ion concentration. The name pH comes from the power of hydrogen. This mathematical transaction provides us with a convenient scale from 0, for an acid solution of unit strength, to 7 for a neutral solution of pure water.

Alkalis owe their alkalinity to the hydroxyl ions ($OH^-$) that they produce in solution.

Alkalinity, measured on the same pH scale as acidity, is expressed as a value from 7 to 14.

Any number below 7.0 is an acid and for each whole number of decline there is an increase in the intensity of ($H^+$ ion concentration) the acid by a factor of 10×. Any number above 7.0 is considered alkaline and for each whole number of increase there is an increase in the intensity of ($OH^-$ ion concentration) the alkaline by a factor of 10×. In a solution with the same number of $H^+$ ions and $OH^-$ ions the pH is 7.0.

Water from the tap may be a little on the alkaline side due to the addition of caustic soda lye to make the water potable. Proper measurement and adjustment of the water is essential to the pretreatment process. The pH of the water is measured by inserting a probe into the water that is attached to a meter. To ensure that the measurement is accurate, the meter must be properly calibrated.

The pH electrode used with the meter must not be allowed to dry off. When not in use the electrode should be soaked in pH buffer solution. The electrode should not be used in solutions above 140°F, and it should be protected from freezing. The electrode should be rinsed with distilled water before being transferred from the test solution to the buffer solution and it should be shaken off to reduce solution contamination whenever it is transferred from one solution to another.

If a coating has formed on the electrode tip, it should be removed by stirring briskly in a detergent solution or by spraying with a squirt bottle. If this does not work and the meter responds slowly or improperly, the glass bulb can be gently cleaned with a soft brush. If it still does not work properly the bulb or meter should be replaced.

The pH buffer solutions should be checked periodically by comparing their pH to the pH of fresh buffer solution. The solution should be replaced when a pH difference of 0.1 or greater is measured.

For proper pH control of a phosphate solution, it is important to establish a desired coating weight and adjust the pH to the level that will provide that established standard. The proper chemical concentration, pH, and temperature should be measured (and adjusted if necessary) at the start of the shift, middle, and end, to maintain the balance necessary to provide the desired coating weight. Because all phosphate products and vendors have there own unique blends, the guidelines provided by the chemical supplier should be followed for proper solution maintenance.

In a seal rinse solution, the variables to be controlled are pH and conductivity. The standard recommended pH level for a seal rinse is based on the chemicals used and the standard for conductivity level is the raw water plus any additional conductivity added by the seal rinse solution. These variables should be monitored along with the other rinses, three times a day.

The conductivity of a DI/RO water rinse should be around 50 μmho for recirculated DI water and 10 μmho for fresh DI water. Manufacturers' guidelines should be followed for maintenance of the DI generation system.

#### 1.7.2.4 Washer Control Methods

Control of the washer solutions can be done by manual titration or with automated systems. Effective control depends on the specific method chosen and the dedication of the people responsible for the washer.

#### 1.7.2.5 Manual Bath Control

A manually controlled line depends on regular titration and the correct additions as needed. Depending on the philosophy of the operators, this could consume more, less, or the same volume of product as an automated controlled system. If the operator checks the washer frequently and adds small volumes of chemistries, the consumption should equal the automated system and performance should be excellent. Larger, less frequent additions should be avoided so that the solution remains fairly consistent. In a manual controlled system, the operator will normally add product using 5-gal buckets. This involves filling the bucket, lifting it to the eye level, and pouring the product into the sump of the stage. Proper personal protection equipment (safety glasses, rubber apron, rubber gloves, etc.) is essential for worker safety.

#### 1.7.2.6 Automated Control Techniques

Regardless of the quality of the chemistries used in the washer, they must be properly adjusted and maintained to perform effectively. Maintenance of the chemistries through titration and measurement of operating conditions such as pH and TDS will provide optimum performance. Any probe used in a chemical solution must be cleaned frequently to provide accurate readings.

#### 1.7.2.7 Metering Pumps

A metering pump will provide a continuous flow of a small volume of product to the bath. The pump can be tied into the conveyor or washer electrical circuits and only operated when the production line is running. The metering pump eliminates slug additions and reduces the handling of the product. Over time, the operator, based on the chemical tests, will adjust the pump output volume to maintain the bath within specification. Metering pumps are a great improvement over manual control techniques and when combined with a chemical controller they provide the best method of process control.

### 1.7.2.8 Theory of Automated Control

As mentioned previously, the best way to maintain a consistent, controlled solution is to make small, frequent product additions as required. A continuous, online chemical controller will activate the metering pump and hold the concentration of chemical in the bath to an extremely tight level for consistent performance. The cost of these controllers is quite low and the quality is excellent.

An automatic controller will not eliminate the need to titrate and perform chemical analysis of the bath, but it may be possible to perform the checks less frequently. The manual checks are still the best method to determine bath chemistry and make sure that the controller is operating properly. Like any instrument that provides a value, that value must be verified for accuracy. Bad information from a controller or any other instrument is worse than no information at all.

### 1.7.2.9 Conductivity Control

As certain molecules dissolve in water, the ability of the resulting solution to conduct electricity is increased. This holds true for most chemistries used in finishing lines. Thus, the concentration of products, such as alkaline cleaners, will be directly related to the conductivity of the bath.

A conductivity controller will measure the conductivity of the bath and when it falls below the target or set point, the controller will activate the metering pump to replenish the bath. The flow rate on the metering pump should be set to maximum so that when the controller calls for product the set point is reached as soon as possible. Some controllers will feed until the set point is reached and others will feed to a preset value above the set point and then turn off the pump.

Many controllers include an alarm function. The alarm mode would activate if the controller calls for product to be added, but the set point was not reached in a predetermined length of time. This could occur if the chemical drum was empty, the feed pump was not functioning, the sensor has failed, or if a float valve was stuck open, feeding fresh water. Alarms can be wired to a lamp or buzzer to alert the operator of the problem. In more sophisticated controllers, the units have diagnostic features, which will internally check the system and display an error message if a problem is noted.

The controller needs periodic adjustment for nonproduct-related conductivity sources such as soil being removed from the substrates or reaction products from conversion coating baths.

### 1.7.2.10 Contacting Conductivity

Contacting conductivity probes have carbon tipped sensors that measure the conductivity of the solution. While acceptable for certain processes such as rinse waters, contacting conductivity sensors in most processing tanks can be easily fouled by soil or scale and quickly yield unreliable information.

These sensors are more sensitive in reading low levels of conductivity than noncontacting probes, but noncontacting or electrodeless conductivity systems provide more effective process control.

### 1.7.2.11 Noncontacting Conductivity

Electrodeless conductivity sensors have been available for considerable time now and have proven their ability to accurately and reliably control most finishing processes. The fact that the sensing elements in this type of probe do not contact the process solution means that these sensors avoid fouling and require significantly less maintenance.

These probes use two "toroidally" wound wires that are encapsulated in the ring- or doughnut-shaped sensor body. The controller supplies current to one of the wires. The second wire has a specific current induced upon it based on the conductivity of the solution in which it is submersed. The controller measures this and calculates the conductivity of the solution. These systems must be temperature compensated. Some systems allow for the input of custom calibration curves for the specific product being measured. These systems allow the option of displaying the units in a percentage value.

Electrodeless conductivity systems are the ideal choice for cleaner baths and conversion coatings. For very dilute processing baths, chemistries with very low conductivity values and rinse waters, contacting conductivity should be used, because they are better at monitoring low levels of conductivity than the noncontacting systems.

For rinse water tanks the controller should be programmed to open a fresh-water feed valve when the conductivity rises above the set point. For DI/RO water systems, a resistivity controller system with the appropriate sensor should be used to handle the extremely low conductivity.

### 1.7.2.12 Zinc Phosphate Control

A standard electrodeless controller is usually effective for monitoring iron phosphate baths. Zinc phosphate solutions have more complex chemistry and require more thorough control techniques. This is especially true of spray zinc phosphate systems.

Zinc phosphate solutions often have multiple products being added to the bath simultaneously, such as accelerators and replenishing packages. In addition, it is often the titration ratio value and not the total or free acid that is used to control the bath. Controlling the process based on the overall conductivity is not reliable.

These baths should be run either manually or with an auto-titrating system capable of running a series of different tests. In a limited number of cases, a conductivity controller can effectively be used to hold the total acid value constant and acceptably control the bath.

#### 1.7.2.13 pH Controllers

pH controllers can be used on certain processes to add product when a set point is reached in either a rising or falling direction. The sensors on pH electrodes are contacting the process solutions. Most of these sensors are semipermeable glass surfaces that are very sensitive.

They require calibration on a regular basis. The best method is a two-point calibration with buffer solutions. In some cases, a single point calibration with a "grab sample" tested on a second, calibrated meter is acceptable. pH control should be verified frequently for reliable results.

#### 1.7.2.14 Interfacing Controllers with a Computer

Chemical controllers are powerful tools and sufficient on their own in most applications. Combining controllers with computers provides a number of additional features that can add benefit to the system. The computer can be used as a data acquisition tool or it can be used to actually control the process.

#### 1.7.2.15 Data Acquisition Tools

Most useful controller systems have an output signal that directly relates to the value of the display. In most cases, this is an analog signal in units of milliamps (usually 4–20). This signal can be directed to a computer where the information can be displayed and stored. The signal is usually digitized using input/output (I/O) hardware and software. Once in the computer, the information can be displayed in several ways. The computer can be networked or accessed remotely to view the data from different locations.

These systems allow for powerful alarming features with varying levels of alarms and can call or page personnel if required and they are ideal for real-time statistical process control (SPC) systems and manipulation of data. They also allow the system to store information that can be reviewed and used to deal with product problems.

#### 1.7.2.16 Computer Control Systems

Computers can be used to actually control the process using programmable logic controllers or a PC with appropriate software from a remote location. Computer-controlled systems can alter the process at any networked or accessed computer station with all of the display and data manipulation features of a computerized data acquisition system.

Recipe functions can be used to allow the operator to activate a program at the terminal that activates a series of events. This can be used to adjust the contact times or temperatures by recipe for different substrates or other variables. In general, these systems use lower cost "transmitters" at the baths in place of controllers and allow the computer to "analyze" the data. These systems can provide complex functions with links to the entire plant operation, from order entry, to inventory, production, and shipping.

Regardless of the type of control system used, strict process control techniques must be practiced to consistently obtain a quality finish. This can be accomplished by simply titrating the baths every 2–3 h or by implementing an automated control process. Learning and understanding each step in the operation and having the ability to measure that the operating parameters of each step is the key to a successful process control system. While automated addition of chemicals is better from the standpoint of process control, the automatic controls must be checked to be sure that they are performing properly. There is no substitute for regular titration.

# 2 Paint Components

A liquid paint is an engineered product made of several different ingredients that mix to create a specific product with its own unique properties. The selection of components used to manufacture paint will affect its stability (shelf life), application characteristics, handling, cleanup, disposal, and most importantly, the performance of the product on which it is applied. Paint formulas usually include

1. Resin (binder)
2. Pigments
3. Solvents
4. Additives

## 2.1 RESIN (BINDER)

The resin is the film-forming component that identifies the paint. A variety of resins and polymers (materials that will undergo reaction to form a resin) are used in paints. The formulation of a paint material and the particular chemicals used are influenced by the particular resin or resin combination used. The blend of resin (sometimes referred to as the binder) and solvent is sometimes referred to as the paint vehicle.

Paint binders may be referred to as convertible and nonconvertible types. Convertible paints are materials that are used in an unpolymerized or partially polymerized state and undergo reaction (polymerization) to form a solid film after application to the substrate. Nonconvertible paints are based on polymerized binders dispersed or dissolved in a medium that evaporates after the coating has been applied to leave a coherent film on the substrate surface.

Convertible binders include oils, oleoresinous varnishes, alkyds, amino resins, epoxy resins, phenolic resins, polyurethane resins, and thermosetting acrylics.

Nonconvertible resins such as cellulose, nitrocellulose, chlorinated rubber, and vinyl resins will not be covered in this text, because they are usually used in low-solid, high-solvent content coatings that are not compliant for the majority of modern industrial applications.

### 2.1.1 OILS AND OLEORESINOUS VARNISHES

Oils were commonly used in paint formulation but have declined as improved polymers were developed that could be used for a broader variety of coatings. With the exception of limited use of refined linseed oil and linseed stand oil in certain types of primers for steel and timber, oils are rarely used as the binder in an industrial paint. However, oils are often used as modifying components in the preparation of oleoresinous varnishes and especially in the oil-modified alkyd resins, one of the most widely used binders in modern paint technology.

Vegetable oils are generally classified as either drying or nondrying oils on the basis of whether they will react with air temperatures to form a rubbery, poor solvent-soluble film.

For example, linseed and tung oil are referred to as drying oils, because they will readily dry when exposed to oxygen. Another group of oils that includes soybean oil is called semidrying oils, because they do not dry as quickly.

Some oils, such as castor oil or olive oil, are classified as nondrying oils. Nondrying oils like castor may be converted to drying oil by heating to 530°F (280°C) for several hours to break down some of the constituent acids of the oil.

The drying process is a complex oxidation reaction involving the centers of unsaturation in the carbon chains of the fatty acid triglycerides of the drying oil. The reaction is referred to as oxidative polymerization or auto-oxidation. Oxidation of a drying oil and film formation will occur naturally, but the rate of reaction is slow and so it is usually accelerated by the addition of driers such as cobalt or lead naphthenates.

Linseed oil as extracted from the flax plant is dull and cloudy and needs to be refined to remove the natural impurities. The method of refining depends on the purpose for which the oil is to be used. The oil can be treated with alkalis, acids, or bleaching processes to lighten the color of the film.

Alkali refining is more commonly used than acid refining. In this process, the oil is treated with sodium hydroxide solution in a calculated quantity to neutralize the acid value of the oil. The acid value is the number of free acid groups in a polymer. The number is actually the milligrams of potassium hydroxide required to neutralize one gram of the polymer. The resultant soap is then removed by centrifuging. The refined oil is then washed with water to remove all traces of the alkaline material. Although certain treatments are needed to clean up linseed oil, it is still used in an unmodified state.

The refined linseed oils are usually low in viscosity and need to be heat treated to produce thicker linseed stand oil. The oil that is processed by heat-treating (520–575°F, 270–300°C) will thicken from polymerization. This makes a more flexible and durable coating, but one that takes longer to dry.

### 2.1.2 ALKYD RESINS

Alkyd resins are modified with a number of oils including soya, linseed, dehydrated castor, and coconut. They in turn can be combined with such resins as acrylics, vinyl toluene, silicones, and amino-resins. The latitude of compatibility of the oil-modified resins makes them popular for use in industrial coatings. They are fairly inexpensive and they have a variety of properties.

Alkyds can be prepared directly from oil (triglyceride), a polyol, or an acid. The percentage of oil contained in an alkyd classifies the end use of the alkyd and affects such properties as speed of drying, flexibility, durability, and so forth. Two manufacturing methods are used in the preparation of alkyd resins: the alcoholysis

**TABLE 2.1**
**Oil Modified Alkyds**

| Alkyd | Oil Length % | Characteristics | Uses |
|---|---|---|---|
| Short | 20–25 | Nonoxidative. Soluble in aromatic hydrocarbon solvents<br>Hard brittle films | As modifying resins in baking systems for interior use |
| Medium | 45–60 | Air-drying or baking cure. Soluble in aliphatic–aromatic solvent blends<br>More flexible films | As above for interior and exterior<br>Also used in fast drying systems |
| Long | 60–80 | Air-drying (oxidative). Soluble in aliphatic solvents. Very flexible films | Exterior air-dry systems |

process, by which oil-modified alkyds are produced, and the fatty acid process, which is used to prepare fatty acid-modified alkyd resins.

The fatty acid resins tend to have a paler color than the oil-modified resins because of the greater purity of the fatty acids. In the fatty acid process, all three components, the fatty acid, the polyhydric alcohol, and the polycarboxylic acid, are heated together at temperatures in the range of 240°C until esterification of polymerization is complete. In the alcoholysis process, the polyhydric alcohol and the modifying oil are first reacted together and then the polycarboxylic acid is added. Both processes yield oil-modified alkyds, classified on the basis of the amount and type of oil used as shown in Table 2.1.

Drying and semidrying alkyds cure by auto-oxidation, so they are good resins to use in formulation of air-dry coatings. Nondrying oil alkyds, particularly the short-oil resins, require exposure to heat for curing. They can also be used as plasticizers for other synthetic resin systems. The composition and simplified structures of a short, medium, and long oil alkyd are shown in Table 2.1.

### 2.1.3 POLYESTER RESINS

Polyester resins are typically used in heat-cured coatings that need to be high in paint solids and low in solvent content. They have extremely good color retention that provides good over-bake protection and very good UV resistance, and they can be applied using a wide range of spray equipment. Polyesters are very similar in chemical structure to the earlier-discussed Type I oil-free alkyd resins. Polyesters are often formulated in two-component products that are used for plastics. The catalyst system in the 2K products allows them to be cured at low temperature, and the finished film has excellent appearance and UV resistance.

### 2.1.4 ACRYLIC RESINS

In the coatings and plastic fields, the term “acrylic” resin applies to the polymers and copolymers of the esters of methacrylic and acrylic acids. Copolymers of these esters with nonacrylic monomers such as styrene, butadiene, or vinyl acetate are also referred to as acrylic resins.

Acrylic resins are very versatile and popular for industrial liquid coatings. They provide toughness, good weathering ability, and resistance to abrasion and chemical attack. They are also considered to be better than alkyd resins for gloss retention. Acrylic thermosetting resins that are cross-linked with epoxy or amino resins are used in the appliance industry because of their excellent physical and chemical properties.

Solid and solution polymers are used in lacquer finishes for metal, wood, leather, ceramic, and plastic surfaces. Acrylic emulsions, which are manufactured directly in the latex form, are used in both indoor and outdoor paints. Along with the stability of the acrylic resins and their toughness and chemical resistance, they also provide an appealing, high-quality coating. The hardness and slip properties can be varied over a wide range to suit the demands of the application. Adhesion and solvent resistance can be built into acrylic coatings by adding other functional monomers into the resin system by copolymerization.

Acrylic polymers are used for decorative and protective functions. For decorative applications, they provide high gloss, good pigment binding characteristics, and clarity. For protective applications, they provide good adhesion, hardness, and durability.

Acrylic lacquers are used for both ferrous and nonferrous substrates. Lacquers are solutions of resins in organic solvents that harden as the result of the evaporation of the solvent. This can be forced or accelerated with heat. The acrylic can be either the major or minor portion of the lacquer.

There are thermoplastic lacquers that allow thermal reflow and better dispersability of metallic colors than thermoset enamels. Applied over a primer and baked, the acrylic lacquers resist many years of outdoor exposure.

Harder acrylics made of almost straight polymethyl methacrylate resin systems are used to make hard, durable finishes for toys. Automotive touch-up lacquers in aerosol cans are another large market. Plastic substrates are a growing market for acrylic coatings, especially since there are now more grades of acrylic polymers that are soluble in solvents that do not attack the plastic. These solvents include ethanol, isopropanol, naphtha, and straight-chain hydrocarbons. The resin systems are usually low to medium molecular weight homopolymers and copolymers of ethyl and n-butyl methacrylate.

Thermosetting acrylics are generally harder, tougher, and more resistant to heat and solvents than the thermoplastics. They are less resistant to UV light and of course, they must be heat cured to obtain cross-linking. Thermosetting acrylics are easier to apply. The relatively low molecular weight copolymers of methacrylate with other acrylic or nonacrylic monomers constitute the uncured resin. These functional monomers provide sites for subsequent cross-linking, usually by reaction with nonacrylic additives. These low molecular weight copolymers make it possible to apply high solids, low volatile organic compound (VOC) coatings, which will level much better before cross-linking and result in a smoother coating.

Most thermosetting acrylic resins available for commercial coating applications contain relatively high amounts of styrene, vinyl-toluene, epoxies, or amine resins to enhance their in-use properties, to lower their cost, or to effect cross-linking. The term "acrylic thermoset" is even applied to coatings that have only the acrylic monomer present to establish the curing or cross-linking sites for the coating. Because of the nonacrylic nature of these coatings, they may not exhibit the characteristic properties normally sought in an acrylic coating.

### 2.1.5 Amino Resins

Amino resins are generally used in baked coatings as cross-linking agents. They are used in proportions up to 50% of the total vehicle binder. They can be used with alkyds, polyesters, epoxies, thermosetting acrylics, phenolics, and other heat reactive resins. Melamine and urea–formaldehyde are the most common examples of this resin.

### 2.1.6 Epoxy Resins

Epoxy resins are known for their excellent corrosion and chemical resistance. Because of their tendency to fade and chalk when exposed to sunlight, they are used for interior topcoat applications or as primer for exterior applications.

Excellent corrosion resistance can be obtained with film thickness as low as 0.5 mil. The epoxy resin is usually cross-linked with melamine or urea resin at curing temperatures of 350–425°F. Epoxy coatings are characterized by excellent adhesion, a high degree of impact and abrasion resistance, and resistance to chemicals and solvents. This combination of properties makes the epoxy formulas a good fit for chemical laboratory furniture and similar applications. They also have good insulating properties, making them a good fit for the electrical industry, and they can provide excellent wear on tools.

Epoxy resins are rarely used as-is in paint formulations because of their low molecular weight. The low molecular weight does not allow adequate film builds, so they are usually cured into higher molecular weight complex polymers called epoxy glycides. The terminal or reactive groups are epoxy and secondary hydroxyl in nature. These complex molecules are then cross-linked with commonly used curing agents.

The most commonly used epoxy paint system is the two-component amine-cured coating where the resin and hardener are mixed just prior to application. The hardener creates a reaction that will create a hardened film after the components are mixed. The pot life (time that it takes for the coating to harden) can range from a few minutes to several days depending on the formulation. Heat is often used in industrial applications to accelerate the cure process.

Epoxy formulas are used as maintenance coatings, can coatings, pipeline coatings, tank linings, and so forth. They have also been formulated using special extenders and thixotroping agents to allow one coat film builds of 6–40 mil. Epoxy formulas are also often used as a primer.

Epoxy resins can also be used in epoxy-acrylic thermosetting systems to provide a combination of film hardness, mar resistance, gloss and color retention, and chemical resistance. These formulas make good coatings for major household appliances and automobiles.

### 2.1.7 URETHANE RESINS

Urethane is the accepted description for a group of polymers that are sometimes called polyurethanes. Urethane resins are very popular with formulators, providing a combination of chemical resistance, toughness and abrasion resistance, and exterior durability. Effective application on plastics has led to substantial growth in urethane technology.

Urethanes are the reaction products of isocyanates with materials that have hydroxyl groups. They contain a significant number of urethane groups regardless of what the rest of the molecule may be. The basic chemistry of isocyanates and urethanes has been known for over a hundred years. In 1848, Wurtz prepared methyl and ethyl isocyanates by reacting potassium cyanate and alkyd iodides. He also found that ethyl isocyanate reacted with ethyl alcohol to form ethyl carbamate, which was later named urethane.

The modern industrial development of urethane polymers stems largely from the pioneering work of Professor Otto Bayer in Germany in 1937. The basic raw materials, the isocyanates, are produced in a number of different forms, but the most widely used is toluene diisocyanate (TDI). The TDI has a noticeable vapor pressure and has an irritant effect on the mucous membranes and so requires special handling.

Table 2.2 compares some of the properties of the various resins discussed.

Many different vehicle systems are used for various applications and environmental conditions with a wide range of properties as shown above.

**TABLE 2.2**
**Resin Properties**

| | Alkyd | Alkyd Amino | Baking Polyester | Modified (Styrenated) Alkyd | Acrylic | Cellulose (Lacquer) | Catalyzed Epoxy | Urethane |
|---|---|---|---|---|---|---|---|---|
| Exterior durability | E | E | E | G | E | E | G | E |
| Salt spray | E | G | G | G | E | E | E | E |
| Alkali resistance | P | F | G | G | G | P | E | F |
| Solvent aliphatic | G | E | E | F | F | F | E | E |
| Solvent ketone | P | P | G | P | P | P | G | E |
| Flexibility | E | G | E | G | E | E | F | E |
| Impact | G | E | E | G | E | E | G | E |
| Heat resistance | G | G | E | G | G | P | G | G |
| Color retention | G | G | E | G | E | E | F | E |
| Gloss retention | E | G | E | F | E | G | P | E |

E = excellent; G = good; F = fair; P = poor.

## 2.2 PIGMENTS

Pigments are particulate solids that are dispersed in paints to provide certain characteristics to them, including color, opacity, durability, mechanical strength, and corrosion protection for metallic substrates. In order to achieve the desired results, pigments have to possess certain properties. Pigments may be inorganic and organic materials. Organic pigments are used primarily for decorative purposes, while inorganic materials have traditionally been added for protective properties. Extenders are used in conjunction with pigments to modify the properties of the paint.

The size and shape of the pigment particles are important considerations, since they affect the agglomeration or packing within the paint binder or matrix. Most pigments are crystalline and the crystal form often affects the characteristics of the pigment. Particle size also affects the finished gloss, settling of the pigment during storage, and wetting by the binder. Other factors such as color, tint strength, colorfastness, and opacity are inherent characteristics of the pigment. Density is another important factor affecting not only settling, but also the volume of pigment for a given weight addition.

Pigments have to be uniformly dispersed in the binder to provide a consistent appearance. They have to remain in suspension or be easy to disperse if settling occurs. When the paint is mixed, the pigments are incorporated mechanically in a mill. The pigment has to be able to withstand the milling process.

A wide variety of coloring agents can be used to provide a considerable range of colors and shades. The number of pigments used and the amount of each is related to color, hiding, and many other film properties. Some common pigments are discussed in the following section.

### 2.2.1 WHITE PIGMENTS

Almost all paint formulas include some white pigments to adjust the lightness–darkness of the final color. Some of common white pigments are listed as follows.

#### 2.2.1.1 Titanium Dioxide

Titanium dioxide is a widely used, nontoxic, stable synthetic pigment used for both protective and decorative paints. It comes in two different crystalline forms, rutile and anatase. The rutile crystalline form is more compact and has a higher specific gravity, greater refractive index, enhanced stability, and enhanced durability.

The high refractive index of titanium dioxide (2.7 for rutile and 2.5 for anatase) enables it to provide a higher degree of opacity in paint films than any other white pigment. Rutile titanium dioxide is photochemically inert and the pigment protects paint films from degradation by scattering absorbed light. In contrast, the anatase form is photochemically active and paints formulated with this pigment are subject to heavy chalking. The anatase grade is used mainly for interior applications due to its cleaner white color.

#### 2.2.1.2 Zinc Oxide

A synthetic based pigment that will inhibit mold growth, if present in high levels (about 30% by weight). The basic nature of zinc oxide leads to interaction with paints of high acid value with the formulation of zinc soaps. These can mechanically reinforce the film but can cause embrittlement on exterior exposure.

#### 2.2.1.3 Antimony Oxide

A synthetic inert pigment often used with chlorine-containing binders in the formulation of fire-retardant paints. When exposed to flames, the antimony chloride vapor that is released is heavier than air and acts as a blanket to the fire. This pigment also has good opacifying characteristics.

#### 2.2.1.4 White Lead

A synthetic basic pigment used for centuries, now limited in use because of its toxicity. Being basic, white lead will react with acidic paints to form lead soaps, which will enhance film elasticity, useful for timber primers. However, the pigment has a high chalking rate and a tendency to darken in polluted atmospheres due to the formation of lead sulfide.

### 2.2.2 YELLOW PIGMENTS

Yellow pigments are used to adjust the yellow–blue axis of the color spectrum.

#### 2.2.2.1 Yellow Dyes

Azo dyes, ranging in color from orange to green-shade yellows. They have good light stability in full shade unless the dye is reduced with white pigments. They provide good opacity and are nontoxic, so they are often used instead of lead chromates. Yellow dyes are soluble in ketones, esters, and aromatic solvents, but they have poor solubility in aliphatic solvents. This makes them suitable for use in air-dry coatings that contain aliphatic hydrocarbons or in emulsion systems.

#### 2.2.2.2 Benzidine Yellows

Insoluble azo dyes prepared in a range of shades from yellow to red. They have good opacity and are insoluble in most solvents used in paint formulations. They are nontoxic and have good resistance to acids and alkalis, and they can withstand temperatures up to 300°F. The benzidine yellows are not lightfast, even when used at full shade, so their use is generally restricted to interior applications.

#### 2.2.2.3 Lead Chromates

Chromate pigments are rarely used today because of the environmental problems associated with chrome. A wide range of synthetic pigments, ranging from pale yellow to deep orange in color, have been used in paint formulation. Lead chromes have high tint strengths, good lightfastness, and opacity, but they also darken in polluted air and they will bleach in the presence of sulfur dioxide. Lead chromates interact with alkaline substrates resulting in color loss. Nevertheless, the lead chromates are useful coloring pigments and are used in undercoats and finishing systems. The color of the pigment is determined by the process conditions during manufacture.

#### 2.2.2.4 Zinc Chromate

Three forms of zinc chromate are used for pigmentation of paints. The pigment grades have good lightfastness and are stable in polluted air, but they are of low opacity. The zinc chromates are slightly basic and will react with acid paints, leading to a thickening of the paint during storage. The form of zinc chromate used for corrosion-protection must be free from residual chloride, which is usually present in pigment grades. A third form of zinc chromate, the tetroxichromate, is used in metal pretreatment primers.

#### 2.2.2.5 Yellow Iron Oxides

Naturally occurring iron oxides, ranging in color from dull yellow to dark yellow-brown, but more restricted in the range of color shades than synthetically prepared oxides. Natural oxides have cleaner and brighter colors combined with greater color strength because of their greater purity. Both natural and synthetic oxides are resistant to alkalis and organic acids, but they can be discolored by mineral acids. Shade variations can occur at elevated temperatures. Iron oxides will absorb UV radiation and have a protective effect in exterior paints.

#### 2.2.2.6 Cadmium Yellow

Synthetic pigments varying in color from primrose to orange, the shade being determined by manufacturing process conditions. They are stable at high temperatures. They are unaffected by alkalies, but they can be decomposed by acids. They may be used on a variety of substrates, especially where alkali resistance or temperature resistance is required.

Cadmium, like chrome and lead, was a staple in the formulation of paint, especially performance coatings, for many years. These heavy metals have long been recognized as undesirable components in paint due to their negative impact on the environment and have been all but phased out of paint formulation in the United States and many other industrialized nations.

### 2.2.3 GREEN PIGMENTS

Green pigments are used to adjust the blue–yellow axis of the color.

#### 2.2.3.1 Phthalo Green

A toner, which, unlike the azo dyes, is not purely organic in nature but is a salt-like compound. Toners are formed by the reaction of a basic dyestuff with a complex acid or by the reaction of an acidic dyestuff with a metal or metal salt; they are more resistant to solvents than the organic dyes.

Phthalocyanine green pigment has a blue–green color with good opacity in paints. It has good resistance to solvents, heat, and alkalis, but it can be decomposed by acids. It is widely used in decorative finishes.

#### 2.2.3.2 Chromium Oxide

Chromium oxide is a dull green, synthetic pigment with good stability to light, heat, acids, and alkalinity, but it provides poor opacity. It is useful as a pigment for paints that requires high chemical and photochemical resistance. Chrome oxide is also used as a pigment for concrete and cement. Once again, chrome is no longer a common pigment used in paint formulation in North America.

#### 2.2.3.3 Lead Chrome Greens

Synthetic pigments ranging from grass green to deep green in color, the shade being controlled by the Prussian blue admixed with the lead chrome yellow. They have good opacity, but they tend to discolor in polluted air. They also tend to float in paint formulations. Owing to toxicity, these products are not often used today.

### 2.2.4 BLUE PIGMENTS

Blue pigments are used to adjust the blue–yellow axis of the color.

#### 2.2.4.1 Phthalocyanine Blues

These vary in color from reddish-blue to yellowish-green; they tend to have high tint strength and high opacity along with very good lightfastness. They are nontoxic, temperature stable, and resistant to most solvents and chemicals except strong acids. These pigments are used in a great many paints and finishes.

#### 2.2.4.2 Prussian Blue

This is a bright blue synthetic pigment having high staining power but low opacity. It is lightfast and acid resistant, but it can decompose to iron oxide by exposure to alkalinity and elevated temperature.

#### 2.2.4.3 Ultramarine Blue

A complex synthetic aluminosilicate pigment, it occurs naturally as the semiprecious stone lapislazuli. The color of the pigment is related to the presence of sodium sulfide. The shade can be altered by the amount of silica used in its manufacture. The pigment has a coarse texture and is subject to hard settling, but it has good lightfastness, heat resistance, and alkali resistance. It will decompose in an acid.

## 2.2.5 RED PIGMENTS

Red pigments are used to adjust the red–green axis of the color.

### 2.2.5.1 Toluidine Reds

Nontoxic azo dyes characterized by bright, clean colors, good lightfastness, and high opacities although the color stability is reduced when they are mixed with white pigments. Toluidine reds have good color stability, are resistant to acids and alkalis, and heat up to 350°F for short periods. They are soluble in aromatic solvents and slightly soluble in aliphatic solvents and alcohols, so they are susceptible to bleeding in many systems.

### 2.2.5.2 Arylamide Reds

Nontoxic azo dyes ranging in color from orange to red or deep crimson. They have good lightfastness even if reduced with white pigments and they are temperature stable up to 300°F. Arylamide reds are slightly soluble in solvents. They are resistant to acids and alkalis and are used in many decorative exterior applications.

### 2.2.5.3 Red Iron Oxide

Natural red oxides, mined as hematite ore, and synthetic red iron oxides are used as pigments. The presence of impurities together with the variation in the iron oxide content provides pigments with colors ranging from orange-red to deep brown. The natural oxides are used in timber stains and low-cost metal primers.

Synthetic oxides have softer texture and greater purity, giving brighter, cleaner colors, and greater tinting strength. Colors are determined by manufacturing condition. Natural and synthetic oxides are resistant to alkalis and organic acids but may react to mineral acids and high temperatures. They absorb UV radiation and increase the resistance of paint films to fading.

Two other inorganic red pigments, red lead and basic lead silicochromate, were used in the past, primarily for their corrosion-protecting properties. They are seldom used today due to the environmental risks associated with such materials.

## 2.2.6 BLACK PIGMENTS

Black pigments are present in many paint formulas to adjust the lightness–darkness of the coating.

### 2.2.6.1 Black Iron Oxide

A synthetic pigment of low tinting strength, mainly used as a colorant for fillers, primers, and undercoats. The pigment is reddened by heat, but otherwise the oxide has good chemical resistance.

#### 2.2.6.2 Carbon Blacks

Pigments that are produced by the carbonization of hydrocarbon minerals, plants, and animals. Properties vary according to the source of the carbon and the impurities present. Purer carbons are of a finer texture, have better color and opacity than carbon of lower purity.

Carbon blacks are lightfast, insoluble in acids and alkalis, and are resistant to solvents. They provide good opacity, even at low addition levels. Carbon blacks are very common pigments used in paint formulations.

### 2.2.7 METALLIC PIGMENTS

Metallic pigments are very popular for paints that will be used on products such as automobiles, motorcycles, metal office furniture, and other products that require exceptional appearance characteristics. While aluminum is the most commonly used metallic pigment, stainless steel, lead, and zinc have also been used in paint formulation.

#### 2.2.7.1 Aluminum Pigment

A pure metal that is rendered resistant to many aggressive agents by the presence of a surface film of alumina. It is available in two powdered forms, leafing and nonleafing grades.

Particles of the leafing grades, which are coated with stearic acid or a similar surface-active agent, tend to float toward the surface of a paint film and become oriented parallel to the plane of the film. The close packed layer of aluminum platelets provides the film with a reasonably efficient moisture barrier and functions as a protective pigment. Normally, low levels of aluminum are used, often with no other pigments. The aluminum may also prevent corrosion by being a sacrificial anode when the surface of the coating has been damaged.

The nonleafing grade does not migrate to the surface of the coating but is more randomly distributed throughout the film. Again, low levels of the nonleafing aluminum are used and the pigment's main function is to provide a sparkle effect to the film.

#### 2.2.7.2 Mica

A naturally occurring potassium alumino-silicate used in the form of fine platelets. The lamellar structure of mica results in a leafing effect like that in leafing-grade aluminum that reduces water permeability in the paint film. The incorporation of mica improves weathering resistance in paint by reducing the tendency to fail by cracking and checking. These properties permit mica to be used in exterior decorative coatings.

## 2.3 EXTENDERS

Extenders are paint additives that are insoluble in the binder and solvents of the formula and have little or no opacity or color effect on the film. They are added to modify the flow and mechanical properties of the paint as well as the, permeability, gloss, and leveling characteristics of the paint film.

### 2.3.1 BARITES

A hard, dense, naturally occurring inorganic mineral that is very resistant to the action of acids and alkalis. It is transparent in oil and resinous media so that it can be used in solvent based paints without affecting the color or opacity of the film. The high specific gravity of barites can result in settling problems in stored paint. It is used as chemically inert filler that reinforces the mechanical properties of the film. It will reduce the durability of the film, if used at high levels in a coating. A synthetic form of barium sulfate is also used as an extender and has properties similar to those of barites.

### 2.3.2 KAOLIN CLAY

A naturally occurring hydrated aluminum silicate used in a fine particulate form. It is used as filler in solvent-based paints but in small amounts, because the small particle size can adversely affect the flow characteristics of the paint. The fine particle size does help to prevent settling in storage. Kaolin clay is used as a flattening agent (gloss reducing) in undercoats and eggshell finish paints and widely used in emulsion paints.

### 2.3.3 TALC

A naturally, occurring hydrated magnesium silicate mineral. It occurs as a mixture of lamellar and fibrous particles, the latter providing a reinforcing effect while improving film flexibility. The platelets have an effect similar to mica in reducing water permeability. As a result, talc is often used in protective paints where high durability is required. The exact nature of how talc and mica improve corrosion resistance is not fully understood.

### 2.3.4 CALCIUM CARBONATE (LIMESTONE)

Naturally occurring limestone that is (also produced synthetically) widely used in interior and exterior emulsion paints and undercoats. Acids will attack limestone, so it cannot be used in aggressive environments. Nevertheless, it has wide usage in both aqueous and solvent-based finishes.

There are many other pigments that will provide corrosion resistance and other properties such as improved adhesion, mechanical properties, and viscosity control. The precise blend selected for a coating is related to the needs of the end user. Color, performance, cost, and environmental concerns affect the particular blend of pigments used.

Figure 2.1 is a pictorial representation of the optimum pigment loading that can be calculated. The common term for this is the pigment to binder ratio. Although everyone talks about pigment to binder ratios, experience has shown that very few paint formulators can actually determine the pigment-to-binder ratio. The optimum pigment loading is generally based on empirical observations, trial and error, and history.

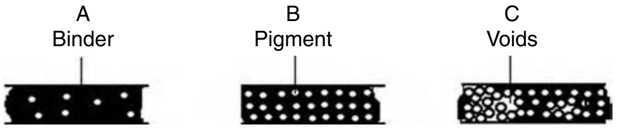


**FIGURE 2.1** Three different pigment to binder ratios.

**TABLE 2.3**
**Usual Variation of Film Properties with Increasing Pigment Levels**

| Property | Usual Effect of More Pigment Levels |
|---|---|
| Viscosity | Increases |
| Adhesion | Maximum at CPVC |
| Tensile strength | Maximum at CPVC |
| Moisture permeability | Minimum at CPVC |
| Cost | Increases |
| Gloss | Decreases |
| Impact resistance | Maximum at CPVC |

Figure 2.1 shows three different pigment-to-binder ratios. The pigment volume concentration (PVC) at which the pigment particles just touch each other with binder filling the space between them is called the critical pigment volume concentration (CPVC). The picture A in the figure has too little pigment, B is the correct CPVC, and C has too much pigment.

The percentage of pigment required to achieve the CPVC depends on the size and shape of the particles. Smaller particles can be packed together with greater efficiency, resulting in higher CPVC.

The significance of PVC is illustrated in Table 2.3. It shows how a number of important film properties vary with pigment level. The amount of pigment in paint is often a compromise between several of the properties listed in Table 2.3.

## 2.4 SOLVENTS

A solvent is a pure or mixed liquid that is used to make the paint flowable prior to its application. In practice, the term solvent, solvent blend, and thinner are often used interchangeably. Solvents are chemical substances that can dissolve, suspend, or extract other materials, usually without chemically changing either the solvents or the other materials. Solvents make it possible to process, apply, clean, or separate materials. Solvents work on the principle of "like dissolves like." Therefore, for a solvent to work, it needs to have similar chemical characteristics to the substance that it is trying to dissolve. Water is also a solvent, which is described as "inorganic" (not containing carbon).

Some important terms relating to solvents are as follows:

- *True solvent*—A liquid that can dissolve the binder.
- *Diluent*—A liquid that cannot dissolve the binder by itself but can be added to a solution to increase its capacity for the binder.
- *Latent solvent*—A liquid that cannot dissolve the binder by itself but increases the binder's tolerance for a diluent.
- *Thinner*—Any pure or mixed liquid added to a paint to reduce its viscosity (make it more flowable).
- *Front-end solvent*—A fast evaporating solvent that leaves the paint very soon after application, usually before the part reaches the oven.
- *Exempt solvent*—Solvents that do not react with sunlight to form smog and whose use is not controlled by regulation. A few chlorinated compounds are now considered exempt as well as acetone and methyl acetate. Review of the status of solvents in ongoing.
- *Middle solvent*—A medium evaporation rate solvent that leaves the paint primarily during flash-off and oven warm-up.
- *Tail-end solvent*—A slow evaporating solvent that leaves the paint primarily during the baking cycle.
- *Retarder*—A slow evaporating solvent added to a paint to prolong the drying time. Typically used to reduce orange peel or blushing.
- *Solvent blend*—The particular mixture of liquids that gives a paint the desired flow or evaporation properties. Skillful solvent blending allows a paint shop to adjust purchased paint for local variation in temperature, humidity, line speed, application equipment, and so forth. The selection of a solvent system is often a complex task, best handled by the paint vendor. Important considerations in blending solvents are solvency, viscosity, evaporation rate, safety, and cost.
- *Solvency*—The ability of the solvent to dissolve the binder. The solvent must be able to keep the binder in solution.
- *Evaporation rate*—The solvent must evaporate within the time allowed by the curing schedule. Available oven length and temperature, as well as production volume is important. If the solvent is a mixture of two or more liquids, their individual evaporation rates become very important. For example, if the solvent remaining on the workpiece should become excessively rich in diluent, the binder might come out of the solution as small sticky lumps, rather than the smooth even film that is desired.
- *Viscosity*—The fluidity or flow-ability of the paint. Paint viscosity is adjusted to provide good atomization and flow-out.

The proper solvent for a given task will depend on the required properties of the formula and other considerations such as safety and cost.

Safety issues affect the solvents chosen for formulation. For example, naphtha-like hydrocarbons are very flammable and chlorinated hydrocarbons are very toxic, so they must be used with extreme care.

Many times, the choice of a solvent system is dictated by simple economics. The purchase price of the solvent is not the only factor here. The cost of handling and disposal must also be considered. These factors help account for the current interest in waterborne and powder coating systems.

Solvents are volatile liquids added to paints to dissolve the binder (the resin component) and/or to modify the paint viscosity. The paint viscosity must be compatible with the storage and application methods.

The solvent must have an evaporation rate that works well in the application environment. Ideally, the solvent should also be nontoxic, of low cost, and have an acceptable odor.

The particular solvents that may work in a given formula will depend on their solubility characteristics. There are three classes of solubility: strongly hydrogen bonded, moderately hydrogen bonded, and weakly hydrogen bonded. Alcohols fit into the first category; ketones, ethers, and esters into the second; and hydrocarbons in the third class. The approximate ranges of these parameters for the various classes of solvent are given in Table 2.4.

The above selection criteria are valid for solvents used for convertible binders. In nonconvertible coatings, solvents have more complex functions, contributing to the coating application characteristics, the drying time, and the properties of the final film. In this case, a blend of solvents is used to dissolve the binder and provide a diluent. The diluent may not be a true solvent for the binder, but it can increase the capacity of the primary (or true) solvent to dissolve the binder. It also costs less than the true solvent so that its inclusion reduces the overall cost of the formulation.

Resins used as paint binders have a range of parameter values that affect solvent selection. The solvent and the binder must be compatible. Epoxy resins, which have a range of 8–13, are soluble in ketones, ethers, and esters but insoluble in hydrocarbons and alcohols because the values are zero.

If a coating needs to be solvent resistant, it will be formulated with a resin that has a solubility parameter significantly different from the solvent(s) that need to be resisted.

**TABLE 2.4**
**Solubility Parameters for Classes of Solvent (Hydrogen Bonding)**

| Solvent Class | Strong | Moderate | Poor |
|---|---|---|---|
| Alcohols | 11–13 | — | — |
| Ketones | — | 8–10 | — |
| Ethers | — | 9–10 | — |
| Esters | — | 8–9 | — |
| Aliphatic hydrocarbons | — | — | 7–8 |
| Aromatic hydrocarbons | — | — | 8–9 |

Typically, compatibility of two or more resins in a coating requires that there is no more than one unit difference in the midpoints of their ranges.

Usually, when selecting solvents for a particular resin, the solubility parameters of the solvents have to lie within the range of the resin. Other selection criteria include cost, paint viscosity, and drying time. A blend of diluent with the primary solvent will usually create a mixture with a mean that is within the mid-80% of the resin solubility range.

The evaporation rate of a solvent is particularly important for nonconvertible coatings. Slow-evaporating solvents may cause long drying times and create problems in batch coating operations or excessive flow and sag of the wet film. High evaporation rates may cause problems with flow and film integrity. Selection is affected by the method of application. Typically, slower evaporation rates are required for brush-applied coatings while faster rates are used for spray methods. Some properties of some common solvents are given in Table 2.5.

## 2.4.1 HYDROCARBON SOLVENTS

Aliphatic and aromatic hydrocarbons are commonly used to formulate and reduce a paint material. They are complex mixtures of different compounds with different flash points, density, and other properties.

### 2.4.1.1 Toluene

Toluene is an aromatic hydrocarbon used in solvent blends for air-drying vinyl and chlorinated rubber coatings as well as a diluent in nitrocellulose paints.

**TABLE 2.5**
**Properties of Some Solvents**

| Solvent | Specific Gravity | Boiling Point (°C) | Evaporation Rate[a] | Flash Point (°C) |
|---|---|---|---|---|
| Acetone | 0.79 | 56 | 944 | −18 |
| Butyl acetate | 0.88 | 125 | 100 | 23 |
| Butyl alcohol | 0.881 | 118 | 36 | 35 |
| Ethyl acetate | 0.90 | 77 | 480 | −4.4 |
| Ethyl alcohol | 0.79 | 79 | 253 | 12 |
| Ethylene glycol monoethyl ether (2 ethoxyethanol) | 0.93 | 135 | 24 | 49 |
| Methyl ethyl ketone | 0.81 | 80 | 572 | −7 |
| Methyl isobutyl ketone | 0.83 | 116 | 164 | 13 |
| Toluene | 0.87 | 111 | 214 | 4.4 |
| Mineral spirits | 0.80 | 150–200 | −18 | 38 (min) |
| Xylene | 0.87 | 138–144 | 73 | 17–25 |

[a] Evaporation rate values based on butyl acetate = 100; these values relate to pure solvents and will be lower where dissolved solids or diluents are present.

#### 2.4.1.2 Mineral Spirits

Mineral spirits are largely aliphatic (but containing 15–18% aromatics) blend of paraffins of variable composition. They are slow-evaporating and dissolves most natural resins, oleoresinous varnishes, and medium- and long-oil alkyd resins. Mineral spirit is commonly used as the main (often sole) solvent for brush-applied decorative and protective paints based on these binders. It is also used as a cleaning and degreasing solvent.

#### 2.4.1.3 Xylene

Xylene is an aromatic hydrocarbon widely used as a solvent for short-oil alkyd, chlorinated rubber, and polyurethane resins. The good solvating power and moderate evaporation rate permit xylene to be used for sag-resistant spray-applied coatings (even of relatively thick films) as well as for baking-cured coatings.

### 2.4.2 OXYGENATED SOLVENTS

Oxygenated solvents include alcohols, glycol ethers, ketones, esters, and glycol ether esters that are synthesized from other chemicals to form a desired solvent that is typically 99% pure.

#### 2.4.2.1 Butyl Alcohol

Butyl alcohol is a slow-evaporating solvent for a wide variety of oils and resins, particularly amino and acrylic resins and also, in solvent combinations for nitrocellulose resins.

#### 2.4.2.2 Ethyl Alcohol

Ethyl alcohol is usually used admixed with methyl alcohol, dyes, and toxins in the form of industrial alcohol (methylated spirits). Ethyl alcohol, a fast-evaporating solvent, is used for poly(vinyl butyryl) as well as with other solvents for nitrocellulose.

#### 2.4.2.3 Ethylene Glycol Monoethyl Ether

Glycol ether is a slow-evaporating solvent for many resins, which is often added to brush-applied formulations that cannot incorporate aliphatic hydrocarbons such as white spirit. The high-boiling ethers are widely used as coalescing aids (solvents) in emulsion paints.

#### 2.4.2.4 Acetone

Acetone is a fast-evaporating powerful solvent used for vinyl copolymers and nitrocellulose. It is also blended (at low addition levels) with many other solvents, when its high solvating power and evaporation rate modify the properties of the liquid paint and the film. They are treated just like water on the HEARS (Health, Environmental and Regulatory Services) program and will be reported as VOC-less exempt solvents.

#### 2.4.2.5 Methyl Ethyl Ketone (MEK)

MEK is a powerful solvent with a fast evaporation rate, widely used for vinyl copolymers, epoxy, and polyurethane systems. It is often blended with less powerful solvents to modify the film-forming properties and application characteristics of coatings.

#### 2.4.2.6 Methyl Isobutyl Ketone

Methyl isobutyl ketone is a fast-evaporating powerful solvent used in similar applications as MEK but where a somewhat slower evaporation rate is required. It is also used at low addition levels in solvent blends where its fast evaporation rate and high solvent power will benefit the properties of the liquid paint and film-forming characteristics.

#### 2.4.2.7 Butyl Acetate

Butyl acetate is an ester solvent, with moderately fast evaporation rate, of general applicability. Formerly butyl acetate was the major solvent for nitrocellulose coatings; it is now used for a wide variety of synthetic resins but is less powerful than the ketone solvents.

#### 2.4.2.8 Ethyl Acetate

Ethyl acetate is another ester solvent with rapid evaporation rate. The major application of ethyl acetate was formerly in nitrocellulose coatings, but it now has a somewhat wider application. It has a lower solvating power than the ketone solvents.

## 2.5 ADDITIVES

Additives are chemicals added to paint, usually in small quantities, to achieve special effects. Although additives have been used in paints for centuries, it is not always understood how they operate. Typical paint additives may be classified by their effect on the properties of liquid or dry paint.

Additives can affect the paint material characteristics and the finished film properties. Examples of properties that can be adjusted with paint additives include viscosity, foaming, skinning, pigment dispersion, stability, flexibility/hardness, gloss, UV resistance, fire resistance, bacteria resistance, and many more.

## 2.6 SUMMARY

Industrial paints are engineered products that include a variety of ingredients to produce the desired results. The coating that works best for a given application is a balance between the needs of the finish and the cost of the coating. The specific requirements for coating appearance and performance are very important to the selection process.

# 3 Liquid Organic Coatings

The resins and other paint components that have been discussed in the previous chapter are used to provide properties to coatings for specific applications. These properties are determined by the substrate to be covered, the end use for the product, and the environment in which the coating will be applied.

There are a tremendous number of industrial and trade sales paints available. Paints are manufactured for industrial applications, building maintenance, house painting, architectural steel, tanks, and bridges. This text is focused on industrial coatings applied to manufactured durable goods.

## 3.1 COATINGS SELECTION

Virtually any desired property can be built into the coating if the need exists. Ultraviolet light resistance, chemical resistance, impact resistance, glossy appearance, smoothness, and many more characteristics can be part of the formula. It is important to carefully define the needs of the end product to be sure that the coating will perform properly. Keep in mind that any special characteristics will probably raise the cost of the paint.

The primary factors to consider in choosing a coating are the task to be performed, (appearance or performance) and the environment the product will be used in.

### 3.1.1 APPEARANCE

- Gloss level—high, medium, low
- Finish appearance—smooth, slight texture or orange peel, heavily textured or spatter coated

### 3.1.2 PERFORMANCE

- UV resistance
- Corrosion resistance
- Abrasion
- Solvent/chemical attack
- Hardness
- Impact resistance

### 3.1.3 OTHER FACTORS

- Manufacturing abuses (forming, machining, or welding after coating)
- Substrate to be coated: plastic, wood, steel, aluminum and castings

- Value of the product and cost per square foot applied
- Exterior or interior use
- Product life expectancy

## 3.2 PAINT CLASSIFICATIONS

There are different ways to classify paint materials based on their formulations and use. The specific task they perform, the physical type of paint they are known as, and other factors may be used to identify a particular product.

### 3.2.1 Paints Classified by Task

Paints are often identified by the task they perform, such as primers, sealers, surfacers, and topcoats. Each type of paint has a different function.

#### 3.2.1.1 Primers

A primer is the first coat applied to a surface. Its usual job is to fight corrosion and enhance the adhesion of subsequent coatings applied over the primed surface. Most industrial primers are cross-linking or thermosetting type.

The binder used in the primer must be compatible with the substrate and the second coat. Thus, different primers are required for wood, stone, metal, and plastic surfaces. Primers must be able to tolerate the differences in thermal expansion between substrate and paint.

When primers are used for protection against corrosion, they are usually highly pigmented. They usually have relatively low gloss, because the primer particles extend up to the surface of the film and give it a rough, pebbled texture. The best corrosion resistance is usually achieved at a pigment level near the critical pigment volume concentration (CPVC). Primer film thickness is typically 1.0–3.0 mil.

Primers for metal are frequently alkyd systems that cure by a solvent reaction mechanism. A typical industrial primer might have the following approximate composition, as sprayed:

- Alkyd resin: 20%—binder
- Pigment: 15%—for corrosion protection
- Solvent: 60%—to liquefy
- Additives: 5%—viscosity control, antifoam, and so forth

In recent years, there has been a trend toward using epoxy-modified alkyd binders for primers. These resins have better adhesion and corrosion resistance than conventional alkyds.

#### 3.2.1.2 Sealers and Surfacers

Sealers are paint films applied between a primer and a topcoat to improve adhesion. This is often necessary if the primer and topcoat have different adhesive, thermal expansion, or impact resistance properties. When the interface between these films is stressed, the layers sometimes separate, and the topcoat can then chip, crack, or break off.

Sealers are also sometimes used to provide a barrier coat between a paint film and the solvent in a subsequent coat. This may be necessary if the pigment in the lower coat has a tendency to bleed into the solvent of the upper coat.

Sealers have special binders that stick well to both the primer and the topcoat. In addition, they are slightly elastic, acting as flexible glue to hold the primer and the topcoat together during periods of mechanical or thermal stress. Sealers are usually low in pigment. Typically, sealers are applied as thin films less than 0.5 mil thick when dry.

A surfacer is a coating used to fill irregularities in the primer. Since primers are often heavily loaded with pigment, they sometimes bake out with rough surfaces that are difficult to sand. A surfacer is designed to be sanded and provide a smooth surface before topcoat application. The typical film thickness for a surfacer is 1.0–3.5 mil.

### 3.2.1.3 Topcoat

The final layer of paint, the topcoat, is the one that provides the necessary appearance and possibly improves performance. Topcoat may be applied as a single coat, or it may be applied as more than one thin coat to achieve the final film build. When several coats are applied, it is not always necessary to completely dry each coat. The first coat is allowed to flash off before receiving the next coat. This is referred to as wet-on-wet application.

The topcoat provides the surface with the desired color, gloss, abrasion resistance, and weatherability. Usually, the corrosion resistance of the topcoat is minimal. The highly pigmented primer is expected to provide most of the paint's corrosion resistance.

Many binders are used for topcoats. The final choice of a topcoat usually requires a trade-off among several properties (Table 3.1). In the automotive industry, for example, it may be necessary to sacrifice some impact resistance to achieve the desired gloss.

**TABLE 3.1**
**Comparative Properties of Common Paint Resins**

| Resin | Moisture Resistance | Chip Resistance | Temperature Resistance | Light Stability | Cost |
|---|---|---|---|---|---|
| Acrylic | Medium | Low | Medium | High | Medium |
| Alkyd | Medium | Medium | Medium | Medium | Medium |
| Asphaltic | High | High | Low | Low | Low |
| Epoxies | High | High | High | Low | High |
| Urethanes | Medium | High | Variable | Medium | High |
| Polyester | Medium | Medium | Medium | Medium | Medium |

**TABLE 3.2**
**Characteristics of Waterborne Formulations**

| Property | True Solutions | Colloidal Dispersions | Emulsions |
|---|---|---|---|
| Molecular weight | 15–50,000 | 20–200,000 | Up to 1 million |
| Viscosity | Depends on molecular weight | Depends on molecular weight | Independent of molecular weight |
| Particle size | Molecules | Less than 0.1 μm | Greater than 0.1 μm |
| % Solids | Low | Medium | High |
| Physical appearance | Clear | Hazy | Milky |
| Pigment stability | Good | Variable | Variable |

## 3.2.2 PAINTS CLASSIFIED BY PHYSICAL TYPE

Paints are also grouped by physical type such as high-solids, waterborne, or powder coating. The following is a description and comparison of the most common types of industrial liquid coatings, high-solids, and waterborne coatings.

### 3.2.2.1 Waterborne Coatings

Waterborne coatings are materials in which water is the major solvent or dispersant. The coating may be a true solution, a colloidal dispersion, or an emulsion. The characteristics of these formulations are shown in Table 3.2.

Waterborne paints contain 5–40% organic cosolvent to aid in wetting, viscosity control, and pigment dispersion. Some systems, especially emulsions, may also contain a polymeric thickener.

Numerous resins are used for waterborne systems. Modified epoxies, polyesters, acrylics, alkyds, vinyl acetate-acrylics, and styrene-acrylics are available. Both thermoplastic and thermosetting (cross-linking) formulations are used. Some resin systems cure when heated while others require the addition of a cross-linking agent.

*Advantages of Waterborne Coatings*

- Reduced fire hazard (some are flammable because of the organic cosolvent)
- Reduced solvent emission
- Lower toxicity
- Use equipment similar to solvent spray

*Limitations of Waterborne Coatings*

- Stainless steel or plastic pipe and fittings are necessary
- Some formulations must be protected from freezing
- Better control of booth temperature and humidity is required
- Longer flash-off times are necessary
- Requires better pretreatment

Waterborne systems are available for most substrates although some plastics may be difficult to wet and have poor adhesion. Color, impact resistance, gloss, weatherability, corrosion resistance, and repairability characteristics of waterbornes are similar to conventional coatings.

There are certain differences from conventional coatings that will affect the plumbing, tanks, booths, and pumps used with waterborne products. These differences are important enough to influence the installation cost and ease of application of waterborne coatings.

Pumps, tanks, and piping must be of noncorrosive material. Black iron systems will corrode, so plastic or stainless steel is recommended due to the composition of the paint. Screens and filters are an important part of the paint distribution system, especially when emulsions are used, and they should be generously sized and regularly serviced. Centrifugal pumps can be used, but positive displacement pumps give better control of pressure and flow rate.

Provisions should be made to keep waterborne coatings from freezing and to avoid storage above 90°F (32°C). The viscosity of many waterborne coatings is temperature sensitive, so paint heaters are often used to ensure good control of this important variable.

Spray booth air velocities for waterborne coatings can be lower than those used for solvent paints, because they contain little toxic, flammable, or bad-smelling solvent. This can provide savings in capital and operating cost. In some cases, booths may need to be longer than usual because of the slow evaporation rate of water. Line speeds may have to be reduced for the same reason.

Keeping the part surface and the spray equipment clean is particularly important with waterborne coatings, because they are less tolerant to oil and dirt. This is because water does not "wet" or "pick-up" these materials as readily as solvents. Even small amounts of oil or grease, which might find its way into tanks, pumps, or lines will not mix with the paint and can cause surface defects on the parts.

Dip systems and air spray systems are commonly used for the application of waterborne coatings. Electrostatic systems are less common. Since waterborne formulations are somewhat electrically conductive, it is necessary to isolate electrostatic systems from ground to avoid loss of current through the supply line.

Temperature and humidity control are more critical for waterborne coatings than for solvent paints, because water evaporates more slowly than many organic solvents.

The slow evaporation rate of water affects several areas of the system:

1. Longer flash-off times are needed
2. Sagging and popping are more likely
3. Wet-on-wet coating may not be possible

In areas where the humidity is very high for an extended period, it may be necessary to air-condition the spray booth to avoid excessive sagging or popping. Air pressure, wet-film build, and gun-to-part distance may also require extra-close attention.

The cure of waterborne coatings is similar to that of solvent paints. The liquids in the film must be driven off in a reasonable time and, in the case of thermosetting enamels, cross-linking is accomplished in an oven.

Waterborne paints must have somewhat longer flash time than solvent-based paints. Sometimes, it is also necessary to use a slower heat-up rate in the oven. If temperature is applied to the wet film too quickly, it may cause popping.

Since water from the paint may be corrosive, it is necessary to use rust resistant panels in the oven and exhaust system.

Once cured, waterborne films are much like other coatings. Overbaking leads to cold-cracking and poor adhesion of subsequent coats. Underbaking means reduced durability and lowered corrosion resistance. The repairability of the finished film is related to the resin and additives in the paint rather than the fact that it is a waterborne formula.

### 3.2.2.2 High-Solids Coatings

High-solids coatings are solvent-based paints that contain greater amounts of pigment and binder than traditional solvent-based paints contain. At least 65% and as high as 85% of the formula is solids content. Ultra-high solids paints may have an even higher percentage of solids. The much lower solvent content of high-solids paints offers some advantages over traditional materials.

#### *Advantages of High-Solids Coatings*

- Less paint must be shipped, stored, pumped, and sprayed compared to traditional solvent-based paint.
- Lower oven-air volumes are required.
- Less paint must be sprayed to provide a given film build.
- Booths may sometimes be shorter.
- Less oven exhaust volume is necessary.
- Less solvent is emitted to the atmosphere. This means less difficulty in meeting regulatory requirements.

#### *Limitations of High-Solids Coatings*

- High viscosity. Paints must often be heated to around 100–120°F to achieve sprayability.
- High viscosity does not perform well in dip tanks or flow-coaters.
- Difficulty in pumping and atomizing, especially when cold.
- Cleaning and phosphating quality may be more important than for conventional paints, because there is less solvent present to “clean as it coats”.
- Sticky over-spray which is messy to clean up, because it remains in the uncured state.

High-solids paints are baking enamels. Alkyds are the most common resins used for high solids, but there are also polyester and acrylic products. Once the paint has been applied and cured, film properties are essentially the same as for other solvent formulations based on the same resin.

Because of the high viscosities involved, high-solids paint lines are usually equipped with paint heaters. Heaters are usually located near the guns and are set to keep the paint in the range of 110–150°F (43–95°C) with tolerance of a few degrees. The elevated temperature drops the paint viscosity enough so that good atomization is possible.

Most spray guns can handle the additional air pressure required for breaking up high-solids paints. However, the capacity of lines, pumps, and filters may have to be increased to ensure trouble-free performance. Pressure-feed pumps are usually required. Paint agitators should be of low-speed, high-torque design rather than the other way around.

Since high-solids paints are heavy (up to 360 kg or 800 lb per barrel), it may be necessary to increase hoist and forklift capacities.

Cure oven exhaust volumes can be lower than conventional solvent-based coatings, because there are less volatile gases in the oven.

Filters and floor papers may need to be changed more often and they are difficult to handle due to the fact that the material may not air-dry.

High-solids coatings are applied with air, airless, conventional, or electrostatic spray. Electrostatic disks and bells are also commonly used. Atomization with these devices is usually excellent at speeds of at least 25,000 rpm.

Film buildup of less than 12.5 μm (1/2 mil or 0.0005″) are possible with 15–30 cm (6–12″) discs. Film builds up about twice as rapidly with high-solids paints as it does with conventional products, so there may be an initial tendency to apply too much paint.

Overspray can be a real nuisance, since it contains about twice as much solids as conventional paint.

Like all liquid coatings, it is important to control the application process and use the right equipment to reduce overspray. Fluid and atomizing pressures, fluid tips, and air caps should be carefully chosen to maximize application efficiency.

Some equipment modifications and operator retraining will be required when converting to higher solids coatings. Larger diameter lines and more powerful pumps are the most common changes required.

The cure of high-solids coatings is similar to conventional enamels. Thirty minutes at 300°F (150°C) is typical although cure schedules can vary considerably. No special ovens are required for high-solids coatings.

Before the paint can be applied, it must be prepared and set up for delivery to the spray system. Good paint preparation and system set up can help to avoid application problems.

When the paint container is first opened, the paint should be checked visually for kick-out. Kick-out refers to the binder coming out of solution as small lumps of soft or hard material. Sometimes, the process can be reversed by agitation, but in many cases the paint is no good. Kick-out results when the binder and solvent are no longer compatible.

The paint should be thoroughly mixed so that there is no separation of the ingredients. Normally, over the course of time, the paint solids will tend to settle to the bottom while the solvents will rise to the top. If applied unmixed, an uneven film will result with differences in film properties. In small batches, the paint can be stirred and in larger operations it is mixed with a powered agitator. To avoid application problems and surface defects, it must be blended to consistent, uniform viscosity.

Proper paint viscosity is critical for obtaining a quality finish. Viscosity is the resistance to flow exhibited by fluids, a result of the internal friction of molecules against each other during movement. In conjunction with air and fluid pressure, viscosity controls the size of the paint droplets when the paint is spray-applied.

Excessive viscosity can cause orange peel while a low viscosity can create a film that is too “wet” and creates runs. A general rule of thumb for application viscosity is 20–25 s on a #2 Zahn cup for conventional air spray and 25–40 s for airless application. However, the product data sheet should always be referred to before application. For high-solids paints, the spray viscosity is usually between 13–20 s on a #3 Zahn cup. Materials and applications vary widely, so viscosity adjustments should be made according to the manufacturers’ recommendations.

The viscosity of the paint should always be checked before and during application. An important factor in checking viscosity is the temperature of the paint. Significant changes in viscosity will occur with relatively small changes in temperature. For example, a coating that has a viscosity of 40 s on #2 Zahn at 70°F could drop to 25 s at 90°F. Viscosities should always be tested at 77°F (25°C).

Viscosity is measured with a viscosity cup and a stopwatch. Viscosity is expressed in terms of seconds of time it takes to flow through the cup that has been filled to a specified level. To take this measurement, the cup is immersed in the paint, filled, and then withdrawn. When the cup is withdrawn from the liquid level of the paint, the stopwatch is started. Paint will flow out of the orifice in the bottom of the cup. The watch is stopped when a definite break in paint flow is seen.

Viscosity is sometimes lowered by reduction with solvent. In some cases, a compliant coating may be delivered ready to spray. Reduction of compliant coatings will reduce the solids content as sprayed and may constitute a violation of an air quality permit. In some cases, it is best to have the coating supplier adjust the material viscosity to make sure that it is not out of compliance.

The relationship of viscosity to temperature can be problem if the spray area does not have climate controls. The plant temperature and humidity will change with the seasons and time of day. This can affect paint viscosity and paint cure characteristics. Different solvent blends may be needed to provide the proper cure during different seasons. Temperature control of the paint can provide the paint consistency needed to maintain proper application viscosity throughout the day. This temperature relationship is illustrated in Figure 3.1.

## 3.3 FILM FORMATION

The resin is the primary ingredient of an organic coating, the part of the coating that forms a film when it dries. The resin is mixed with other ingredients to create an

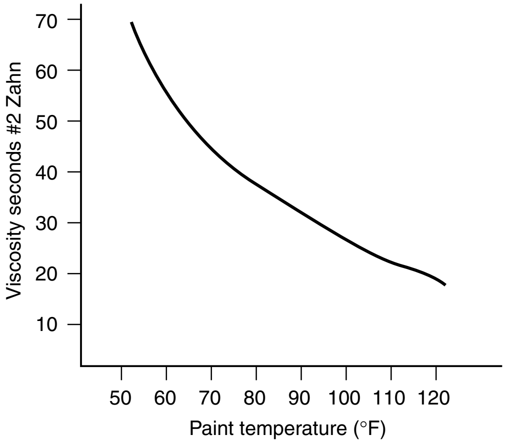


**FIGURE 3.1** Paint viscosity at different temperatures.

engineered product for application. As the coating is applied, it will flow and stabilize into a relatively uniform film. This stage is referred to as fixation. After the coating has stabilized, it will be cured by time, temperature, or some other means.

### 3.3.1 APPLICATION

Application is the spreading of the composition into a thin layer over the surface of a product. Many methods of application can be used including a brush, a roller, a spray gun, curtain coating processor, or electrodeposition system.

The method of application and effective process control will determine the thickness of the coating, uniformity, and efficiency. The application equipment and set-up must be compatible with the particular viscosity and flow characteristics of the coating to provide uniform and consistent results.

### 3.3.2 FIXATION

During fixation, the coating is stabilized so that it will not run off or form an uneven layer on the painted surface. Fixation usually occurs by evaporation of volatile solvent from an organic solvent system or of water from a latex system. Rheological resistance to flow grows within the film as the nonvolatiles concentrate. Fixation may also result from thixotropy built into the paint by the formulator.

An ideal liquid paint would be free flowing during application, flow evenly over the work surface, stabilize quickly, and remain in place. In reality, there is a time interval between the flowing and the nonflowing states. A paint material may never actually be completely free flowing. In many cases, some resistance to flow has to be built into the paint to avoid sagging on the work surface.

Several conditions affect the formulation for flow.

- The solvents used must have sufficient dissolving power for the resin in the paint.

- The desired final dry-film thickness and the number of coats.
- The amount of surface texture that can be tolerated.

The behavior of the film is affected by the rate of evaporation of the solvent mix and the rheology built into the paint.

### 3.3.2.1 The Evaporation Factor

Some house paints that are formulated with raw and modified vegetable-type oils are low enough in viscosity to be free flowing without solvent addition. However, most other coating compositions need solvent to fluidize the solid resins in the binder. The solvents used to blend the coating evaporate at different rates during application and drying.

In the simplest model, evaporation takes place through at least two mechanisms. One is solvent evaporation from the surface of the film that is similar to the same factors as evaporation from the surface of the pure solvent by itself. The other is solvent diffusion from within the body of the film from the lower depths to the surface. The rate of solvent evaporation can affect fixation.

Some problems can occur during solvent evaporation. The rapid cooling effect that occurs as solvent evaporates from the applied film will also cool water vapor in the atmosphere around the paint film. If its vapor pressure is higher than the saturated vapor pressure of water at the surrounding ambient temperature, it will cause condensation on the paint film. The condensed moisture is trapped in the coating where it can cause a white discoloration called solvent-blush.

Another problem sometimes experienced during spray application is dry spray. If a particular solvent evaporates in the atomized paint stream before it reaches the surface of the part, it may affect the flow-out of the coating and create a grainy appearance. Dry spray is often caused by problems with spray technique (gun too far from target), but it can also be a result of using the wrong solvent or the incorrect volume of a particular solvent.

### 3.3.2.2 Rheology

Even a material with high viscosity will tend to flow downward on a vertical surface. A paint material needs some physical structure to prevent sagging. Finely divided powders that make up the pigments and extenders in the paint can provide physical structure through thixotropy.

When stirring causes a temporary decrease in viscosity, the paint is said to be thixotropic. The more vigorously a thixotropic paint is stirred, the less viscous it becomes. The viscosity will go up again if the stirring is stopped.

Thixotropy is often due to reversible flocculation of pigment. If the pigment flocculates without settling, the network of loosely associated particles resists the movement of a brush or stirring paddle. As the brush or paddle is forced through the liquid, the flocculated structure breaks down and allows the liquid to flow more easily. Once the stirring has ceased, the particles again form a network in the container. The network restores “body” to the paint and the viscosity increases.

When mechanically disturbed, such as agitation during application, a thixotropic composition thins out to become comparatively free flowing. Left in an undisturbed state, it will build up structure over time. The time, depending on the actual composition, may be a fraction of a second, minutes, or even hours, and the ultimate level of structure may be low or high. Thixotropy may therefore be harnessed to provide a nearly ideal coating, free flowing during application but rigid immediately thereafter.

A coating needs to be uniformly mixed to perform properly. There are other conditions commonly encountered in a coating where ingredients separate due to flocculation, settling, or kick-out.

#### 3.3.2.3 Flocculation and Settling

Flocculation is the formation of loose clusters of pigment particles in a liquid paint. A certain amount of flocculation is desirable in a paint, because it gives the liquid more "body" than what it has with isolated pigment particles and helps resist sagging. Flocculated pigments that have settled to the bottom of the paint container may sometimes be successfully blended back into the material unless they form hard, compact layers.

#### 3.3.2.4 Kick-Out

The term "kick-out" refers to the binder coming out of solution as small lumps of soft or hard material. Sometimes the process is reversible, but more often the paint is ruined. Kick-out results when the binder and the solvent are no longer compatible. The binder may kick-out if the wrong thinner is used. Kick-out usually occurs because a paint is too old and the binder has chemically changed to the point where it is incompatible with the original solvent blend. This is one reason why the oldest paint in stock should be used first.

### 3.3.3 CURE

Fixation is followed by cure. Fixation and curing may be combined or overlapped. Common lacquers combine fixation and cure in the evaporation of solvents during and after application. A catalyzed paint material begins to combine fixation with curing.

Some coatings are in or near their final state of cure when they complete the fixation period. Lacquers are a broad group of coatings that cure by solvent evaporation alone.

Many coatings need thermal energy or light energy to cure. Thermosetting products are very common for industrial applications.

#### 3.3.3.1 Air Dry

In an air-dry coating, the formulator sets the period of cure with the proper blend of drier catalysts. As a rule, the oxidation process does not start as soon as the paint is spread and exposed to the air. An introduction period is involved, after which the unsaturated vegetable-type acid esters in the paint start to absorb oxygen to create chemically reactive sites in the constituent molecules. These molecules combine to form larger molecules, which result in a paint film.

Actually, the drying process never stops. It slows down greatly and must be controlled to avoid the ultimate formation of an excessively brittle film.

An increase in temperature will increase the rate of the chemical reaction. Curing processes that take place at normal temperatures do so much faster under the influence of heat.

### 3.3.3.2 Catalyzed Materials

Catalyzed materials have two major or more constituents that will begin a curing reaction when they are mixed together. The cure time varies and temperature may vary, but is possible to reach full film properties, even at room temperature. Application of heat will accelerate the cure cycle.

Obviously, the coating components are separately packaged until they are blended for application. A catalyst may be added, if it cannot be included in one of the components. Catalyzed materials are typically very durable coatings.

One example of a two-component coating is the epoxy-polyamide system. Epoxy resins are chemically reactive oxygen atoms that are bound in the molecule to two adjacent carbon atoms to form a three-part ring. Such rings are sensitive to a number of other reactive groups. The polyamide resins are low-molecular-weight relatives of the nylons. Their amide groups can tie up rapidly at room temperature with epoxy groups to form large, bulky molecules that are excellent binders in coatings.

### 3.3.3.3 Baking Enamels

Some coatings do not cure at room temperature and fortunately remain stable in the paint container for extended periods. They convert rapidly (in a fraction of an hour) when exposed to heat. Typical temperatures for baking enamels range from 280 to 350°F (135–175°C) for 10–30 min.

Amine resins are one of the many convertible coatings of this type. Broadly speaking, they divide into urea–formaldehyde derivatives and melamine–formaldehyde derivatives. When heated, these products can become brittle, so many common baking enamels are formulated with plasticizers, such as alkyd resins.

High molecular weight variations of certain resins are tougher and more durable but unfortunately much less soluble than their chemical counterparts of lower molecular weight. Therefore, even though they would provide excellent finished films, these high molecular weight materials cannot be dissolved in solvents.

These high-molecular-weight resins in fine powder form can be mixed with pigment and with a nonvolatile liquid to yield a tough, durable coating. The nonvolatile liquid serves as a plasticizer for the resin. When it is heated, the resin will soften and create a matrix that includes the plasticizer and the pigment. These materials are called plastisols and are commonly based on high-molecular-weight polyvinyl chloride and related polymers. This is cure by fusion.

If the plastisol mixture is too high in viscosity to be properly applied by the selected method, it may be thinned with a minor amount of solvent for the plasticizer.

These variations are called organosols. After the solvent evaporates from the film, the cure is also by fusion.

A coat of latex paint dries in two stages. First, the water evaporates and all the ingredients, other than the latex globules, are concentrated in the space between the globules. These become more closely packed in a geometric array and ultimately touch each other. The film at this juncture has no particular strength and may be easily wiped away.

Second, if a latex film is warmed sufficiently, the globules will sinter at their points of contact and form a hardened coating. Of course, it is not practical to apply heat to paint on a wall. Fortunately, it is possible to design latex compositions that coalesce at ordinary ambient temperatures. It is possible to create latex-based systems in which coalescence does not take place in the bulk package in storage but proceeds smoothly once the coating has been applied as film.

Cure is a relative term. What may be an adequately cured film for gentle handling may still be raw in respect to solvent attack. Many methods are available for testing the degree of cure. The individual end use will dictate the most appropriate method.

### 3.3.4 DRY FILM PROPERTIES

Once the paint is cured, the concern switches to dry film properties. In some respects, the properties of a dry paint film are the most important of all since it is the dry film, which is exposed to the service environment and to the customer's inspection.

#### 3.3.4.1 Gloss

A high-gloss surface reflects nearly all of the light that falls upon it. Reflection of more than 90% of the incident light is possible with modern industrial finishes. High gloss requires a smooth surface. Surface roughness results in scattering of incident light and low gloss. Smoothness can be obtained by polishing or by using processes that allow the paint to dry smoothly without cracks, wrinkles, pinholes, or protrusions. Highly pigmented paints often have low gloss, because pigment particles extend through the surface and reduce smoothness.

Gloss can be manipulated by addition of ingredients that provide hazing to reduce reflection or smoothness to increase reflection.

#### 3.3.4.2 Hiding Power (Opacity)

The ability of a paint to cover a surface and mask it from view is referred to as hiding power. Since most paint binders are transparent, the job of hiding the surface falls primarily to the pigment. Pigments contribute to hiding power in three ways. They may reflect, refract, or absorb the light that enters the paint film.

With reflection and refraction, the light is turned back out of the film before it reaches the painted surface. Figure 3.2 illustrates reflection, refraction, and absorption by a paint film.

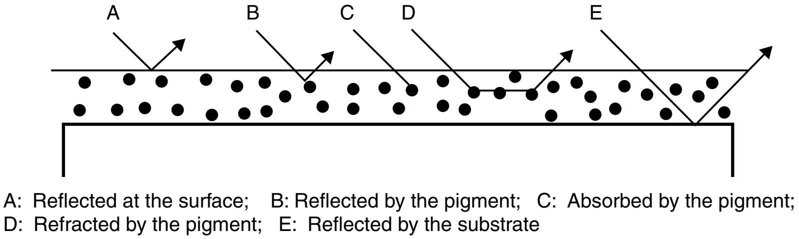

A
B
C
D
E
A: Reflected at the surface; B: Reflected by the pigment; C: Absorbed by the pigment;
D: Refracted by the pigment; E: Reflected by the substrate

**FIGURE 3.2** Light behavior on a painted surface.

### 3.3.4.3 Color

The color of a paint material is primarily due to the pigment interaction with light. Ordinarily, white light is composed of all the colors visible to the human eye. Pigments have the ability to absorb some of these colors and reflect or transmit others. The paint film will be the color of the reflected or transmitted light. Therefore, the pigment in a red paint absorbs all colors except red.

Pigments can be mixed to give colors different from the pigments themselves. A white pigment is often added to a paint to give a lighter color. The difference between a light and a dark blue is often the presence of white titanium dioxide particles in the film with dark blue pigment.

### 3.3.4.4 Strength, Hardness, and Brittleness

These terms describe important properties of a dry paint film. They depend on how effectively the binder molecules, pigment particles, and additive materials attract one another. When there is high attraction between components of a paint material, the film will be strong, hard, and able to resist bending and stretching. This is not always desirable. Such strong, hard films may not be able to bend or stretch and recover under ordinary use conditions. The paint must have some resiliency or stretchiness, because the solid surface under the film may shrink and expand due to temperature changes in the surrounding atmosphere.

Brittleness is the tendency to crack under impact. Paint is brittle when it cannot deform in response to a mechanical stress. This inability to deform, results from excessively high attractions between the paint components.

The degree of attraction between the binder and the pigment can be controlled by the nature of the materials themselves and by the use of additives.

Paint binders may be linear or cross-linked. Linear binder molecules are like randomly intertwined strands of spaghetti. They are generally softer, more flexible, less brittle, more soluble, more water permeable, and less heat resistant than cross-linked binders. Cross-linking means that the linear, threadlike binder molecules have become laterally bonded together at various positions along their length. The resulting 3-D networks are usually stiffer, harder, more brittle, less soluble, less water permeable, and more heat resistant than linear binders are.

Binders are often classified on the basis of their heat behavior. Linear binders that can be melted are called thermoplastic. Cross-linked binders that do not melt are called thermosetting. Most primers and many industrial topcoats have thermosetting binders while sealers and some topcoats are linear binders.

A high degree of pigmentation gives strength and stiffness to a paint film. This is because the pigment particles can act as a load-bearing part of the film and also because the particles resist movement within the film.

Another means of controlling strength, hardness, and brittleness is by the use of additives. Plasticizers weaken, soften, and decrease the brittleness of a paint film. They are small molecules that are thoroughly mixed throughout the film and separate the binder molecules and pigment particles from themselves and from each other. This separation reduces the attractive forces between the paint components and provides a more flexible, softer, less brittle film. Because plasticizers are small molecules, they have a tendency to slowly evaporate from the film over a period of months or years. The result is that many paints tend to become harder and more brittle with age.

#### 3.3.4.5 Depth of Color (Metal-Flake Paints)

Some industrial paints are formulated to give an appearance of depth. Automobiles are usually finished with metallic coatings designed for depth of finish. The depth-of-color look comes from small metal flakes scattered throughout the paint. These flakes, which are usually aluminum, reflect light back to the surface and out of the film. Although the flakes are too small to see individually, they give the effect of light coming from various depths within the film. The paint will have a dazzling or sparkling appearance.

### 3.3.5 HOW PAINT WEARS OUT

All paint films are semipermeable layers that are susceptive to wear. Exposure to the atmosphere, physical abuse, sunlight, water, corrosives, and general wear will cause discoloration, loss of gloss, cracking, chipping, or peeling from their substrate. The three greatest natural enemies of a paint film are sunlight, moisture, and temperature changes.

1. Ultraviolet radiation degrades the binder molecules by breaking bonds between atoms.
2. As binder molecules shrink, film strength declines and moisture penetration increases.
3. With temperature cycling, the moist paint film is first heated and then cooled. The accompanying expansions and contractions put a strain on the film that is poorly resisted, because the binder molecules are now smaller and mechanically weakened.
4. The weakened film surface is now subject to mechanical rub-off and water wash-off.
5. As the unpigmented surface film wears away, the pigment particles become exposed to the elements. Continued degradation of the binder may actually set the pigment mechanically free, at which point the paint begins to chalk.

6. Once exposed to sunlight and moisture, many pigments begin to fade and lose gloss.
7. These changes occur because of a gradual loss of plasticizer from the film that makes it more brittle. The stiffening film is less able to resist the strain of thermal expansion and contraction. Microcracks form and allow moisture to penetrate. This exerts a lifting pressure when warmed by an increase in the surrounding air temperature.

Water can more easily penetrate a weakened film. The overall result is that the paint film gradually erodes away.

# 4 Paint Manufacturing Process

When paint was first discovered in ancient days, it was produced by mixing a natural resin from a plant or tree with natural colorants from the earth or plants. The ingredients were mashed together in some type of container. It was not very durable, but it allowed people to create art and illustration. Modern paint manufacturing is much more sophisticated, but it still involves a blending process to disperse pigment into a vehicle system.

The vehicle system, typically a resin or a varnish type material, is first charged into a mill with thinner and grinding aids. Pigments and extenders are added. The mill is then operated until the pigment particles are broken down and uniformly dispersed to create a grind paste. The grind paste is extended with additional resins and thinner and dropped into a thin-down tank. There, other materials are added to the tank to make the finished product. At this point, a sample of the material is brought into the quality control laboratory and a number of tests are conducted to compare the batch versus the standard parameters it is designed to meet. Trained technicians evaluate the results and then make adjustments for color matching and other characteristics such as viscosity and gloss. In addition to the normal adjustments made to batches, quality checks are performed throughout the manufacturing cycle.

When the paint in the tank meets all the prescribed specifications, quality control approves it for filling. The paint is then filtered to strain out any large or unwanted particles and filled into containers.

The most critical operation in the manufacturing process is the paste grinding process. This is where the solid pigments are broken down into their finest particle size in the resins, solvents, and additives (the vehicle system).

## 4.1 EQUIPMENT USED FOR PIGMENT PASTE MANUFACTURING

The equipment used to grind the pigment is an important part of the process. Different mills work well with different pigment materials.

### 4.1.1 High-Speed Mixers (HSD, HLM)

Among the different types of mills used for grinding, the most widely used is the high-speed disperser (HSD). This mill consists of a tank that is jacketed for cooling water, a motor, and a shaft with an impeller that resembles a saw blade with teeth that are bent 90°.

The dispersion is achieved at or near the surface of the impeller by the violent changing of direction of the mill paste. This shearing action is used to handle easily dispersed pigments such as those found in whites and light pastel colors.

An HSD is used in conjunction with the continuous mill (COM) to premix the mill paste. Both the sand mill and COM are used for the more difficult dispersing pigments such as those found in blue, green, and red colors.

These mills use a variable speed saw-tooth blade rotating at high speed. Peripheral speeds range from 3000 to 6300 ft/min. HLM mixers also have a slow speed sweep agitator at the tank wall to aid in movement from the tank walls.

- *Critical parameters*: paste viscosity, RPM of shaft, and level of paste in the tank (optimum range 2.0–2.5 times blade diameter)
- *Advantages*: requires least amount of labor, easy cleanup, and low maintenance
- *Disadvantages*: high power consumption, easy dispersing pigments needed, and generates heat
- *Typical products*: latex, some primers, plastisols, high solids polyesters, polyurethanes, and acrylics

### 4.1.2 VERTICAL OR HORIZONTAL CONTINUOUS MILL

Another device is a COM. It is also charged with glass or ceramic media and disperses by shear and attrition. In this case, the degree of dispersion is determined by the flow rate of the premixed paste through the COM. These mills have a high-speed shaft with multiple discs of various configurations rotating in a long chamber filled with beads.

- *Critical parameters*: high-throughput rates, easy to clean, low yield losses, and large batch size
- *Disadvantages*: requires premix tank, expensive to maintain, and cannot grind tougher pigments in one pass
- *Typical products*: primers, polyurethane, water reducible (W/R) primers, clean colors, alkyds, and lacquers

### 4.1.3 SAND MILL

Another type of grinding device is a sand mill. It uses a different type of impeller, and it is charged with glass or ceramic as a grinding media. Pigments are ground by shear and attrition and the finesse of the dispersion is determined by the length of time the paste is in the mill, or residency time. This mill consists of a high-speed shaft with one or two solid disc impellers rotating off center in a cylindrical tank with a cone-shaped bottom, filled with small grinding beads.

- *Critical parameters*: ratio of paste volume to media volume and paste viscosity; impeller speed = 3500 ft/min
- *Advantages*: can grind most pigments, low maintenance

- *Disadvantages*: batch operation—requires many mixes, slow discharge, yield loss high, and cleanup is difficult
- *Typical products*: high-solids polyesters, plastisols, water-based baking enamels, alkyds (light colors), and lacquers (light colors)

### 4.1.4 ROLL MILL

A roll mill, another milling device, can use two or more rollers to blend the paint ingredients. The material to be milled is placed between the feed and center rolls. Each adjacent roll rotates at progressively higher speeds. For example, the feed roll may rotate at 30 rpm, the center roll at 90 rpm, and the apron roll at 270 rpm. Material is transferred from the center roll to the apron roll by adhesion. The dispersion is achieved by the shear forces generated between the adjacent rolls. The milled material is removed from the apron roll by a knife that runs against the roll.

- *Critical parameters*: roll pressure, roll clearance, paste viscosity, and tack
- *Advantages*: can grind concentrated pastes with high polyvinyl chloride (PVC) loadings, no wash needed, very fine dispersions obtained, and no metal contamination
- *Disadvantages*: requires premix operation, slow process, and expensive to maintain
- *Typical products*: electrodeposition paste, high-solids polyesters, alkyds, and acrylics

### 4.1.5 BALL MILL

One of the older types of milling equipment that is still used is the ball mill. This mill consists of a cylindrical tank mounted horizontally. It is loaded to one-third of its apparent volume with $5/8''$ steel balls as a grinding media. There are lifter bars located on the inside wall of the mill and as the mill rotates the balls are lifted and then cascaded downward, dispersing the pigment by attrition and shear. These mills are used for the most difficult pigments to disperse such as blacks and organics.

- *Critical parameters*: ball charge = 33% of mill volume; normal paste charge = 25–40% of mill volume
- *Advantages*: no premixing required, no solvent loss, low maintenance, and can handle hard grinding pigments
- *Disadvantages*: long grind times, limited batch size, discoloration from metal, yield losses, and difficult to clean
- *Typical products*: primers, high solids polyesters, alkyds (dark colors), acrylics (colors), acrylics (colors), and lacquers (dark colors)

After the paint is milled, it is filtered and put into containers. Filtration methods vary, depending on the paint material and the needs of the customer.

# 5 Color Matching and Color Control

The appearance of a finished product is often one of the most critical aspects of quality. The way it looks has a significant psychological impact on the perception of quality by the potential customers and on their willingness to buy the product. Color is the most important appearance attribute of an object. There are other attributes such as size, shape, gloss, and texture, but color is by far the most important.

Color, gloss, and texture are imparted to a product by a coating. The coating manufacturer has the responsibility for formulating an accurate color match based on the customer's sample. The applicator also plays a role in accurate color match, since mixing, storage, application, and curing can impact color. It is necessary for the manufacturer to have a quality control program for the desired color and appearance of their product. But it is equally important to be able to detect all sources of error that affect color and appearance.

Color match is usually judged by visual evaluation in standard lighting. Some will use color difference measurement devices as well. An inspector will compare the color of the product to a color standard sample.

If there is some color difference, it will be necessary to judge if it is within acceptable tolerance levels. When there are guideline panels that represent the maximum allowable color difference limit, the task is a little less difficult. Any difference in gloss or texture will further complicate the visual process, because the color match will vary as the angles of view and illumination vary.

Usually, the coating is checked for color by the quality control lab before the customer uses it. A number of sources of error can cause a poor match.

Examples of sources of error:

1. Different color standard
2. Metameric color standard
3. Metameric batch
4. Gloss difference
5. Texture difference
6. Observed metamerism
7. Panel preparation differences
8. Substrate differences
9. Film thickness variance
10. Disagreement between color measuring instruments

In addition to these items, it is possible that the paint needs to be adjusted for accurate shading.

A color difference measurement can provide accurate numerical color match or define a difference from the specification. When measurement equipment is not used, it is hard to describe the visual difference and make an adjustment.

## 5.1 COLOR VARIABLES

Color has three visual variables: hue, saturation, and lightness. Hue is a color variable denoted by red, orange, yellow, green, blue, violet, and purple. Saturation is the variable of color that denotes its purity or its degree of departure from grayness. Lightness is the variable of color that distinguishes black from white, without regard to hue, as represented by a neutral gray scale ranging from black to white.

Hue, saturation, and lightness are often called the three dimensions of color, because it takes a three-dimensional space to represent them. Lightness is distance along the vertical axis, saturation is radial distance away from the vertical axis, and variation in hue is angular distance around the vertical axis.

Color matching is the process of selecting colorants to match a given color and adjusting their concentrations until the hue, saturation, and lightness of the trial (batch) match the hue, saturation, and lightness of the given color sample.

Knowing that color has three variables, leads to the four-colorant principles of color matching. To match a color, hue, saturation, and lightness must be adjustable or controllable and can only be done with a minimum of four colorants. For example, if only one colorant—white—is used, there is no way to change it. It can only be white. By adding black as a second colorant and varying the concentration of the white and black, any number of colors, varying essentially only in lightness can be made. By adding a third colorant, for example red, any number of colors can be made, varying in lightness and saturation but all having essentially the same red hue. By adding a fourth colorant, yellow, then all three color variables—hue, saturation, and lightness—can be varied, and a color can be matched exactly.

If a color is formulated with less than three, then the match can only be obtained when all of the colorants are exactly as they were originally. There is no latitude for production variation. If more than four colorants are used, then it becomes more difficult to determine which colorant will correct a hue difference, a saturation difference, or a lightness difference, because two colorants in a five-colorant formula will control the same variable. For example, a green made with white, black, blue, and two different yellow pigments, needs to be more yellow. Which yellow is added? Some yellow pigments will make it more yellow but also less saturated. Other unsaturated pigments may be more effective in correcting the hue without affecting the saturation. To correct the hue, the effect on saturation must be considered.

## 5.2 METAMERISM

Another reason why a five- or more-colorant formula should not be used is metamerism. Metamerism is when the colors match under one set of illuminants, observer, and viewing conditions, but do match under another. To prevent this, the match must not only contain the same colorants but also the concentration must be the same. In a five or more colorant formula, it is almost impossible to produce batches repeatedly, with the colorants at the same concentrations. Color may not always be controlled. A four-colorant formula is unique, because only one set of concentration of the colorants will produce a match and therefore no batch-to-batch metamerism is possible.

When matching colors by the visual approach, the color matcher selects the colorants by trial and error, experience, and knowledge of subtractive color mixture. It does not take long to learn that mixing blue and yellow together can make a green color. Colorant adjustments are made until the appearance is correct. Blue, black, or some other color is added until a match is made. A quantity of a colorant is added and the change in color is evaluated. If more is needed, the amount is estimated by that change. This process is repeated until a satisfactory match is obtained. With good technique and accurate weighing of colorants, an experienced color matcher can make a match fairly quickly.

The problem with the visual approach is that the matches may be metameric, which may or may not be acceptable. The metamerism occurs because the colorants used are different from those that were used to produce the color sample.

There are three types of metamerism: illuminant, geometric, and observer. Illuminant metamerism is what is normally thought of when the word metamerism is mentioned, a change of light that causes a change of color.

Geometric metamerism is when the colors will match only at a certain angle of viewing and illumination. This is caused by difference in gloss and/or texture. A flat color will only match a gloss color at one viewing angle.

Observer metamerism is when colors are a match for one observer and not for another. It is caused by differences in the color vision of the observers and is quite evident when illuminant metamerism also exists. When there is difficulty in getting a match accepted by a customer, it may very well be observer metamerism.

Dr. Henry Hemmendinger is a leader in understanding the breakdown of a color match by change of either illuminant or observer. Hemmendinger and Davidson developed the D&H Color Rule, a device to quantify the extent of observer metamerism, which is still viewed as an indispensable aide in teaching the principles of observer metamerism. Dr. Hemmendinger, also developed methods to use metameric pairs as tools to assess instrument performance. An observer can readily get a match with highly metameric samples. The pairs chosen are noted and compared to the pairs chosen by another observer. If the pairs are the same under the same light source, the observers have the same color vision. If the pairs appear different under the same light source, it indicates a difference in color vision between the observers.

Visual color measurement is done in a light booth such as a Macbeth Spectralite. This light booth provides three light sources that are commonly used to visually evaluate color and color differences. They are North Daylight, Incandescent, and Cool White Fluorescent (CWF). The International Commission on Illumination (ICI) has standardized on North Daylight and Incandescent and given them the designations illuminant D65 and illuminant A, respectively. CWF has no standard as yet.

The important feature about the booths is that they supply a light source that is constant. Natural daylight varies with the time of day. In addition, metamerism can be evaluated very readily, because two different light sources are provided.

Two ASTM (American Society for Testing Materials) standard practices—D1729, Visual Evaluation of Color Difference of Opaque Materials and D4080, Visual Evaluation of Metamerism—are methods that recommend the use of light booths.

When matching a color where metamerism is obvious, the match under daylight may look like it requires red to correct it, but under incandescent it needs green. When there is no concern about metamerism, color match is done under one light source, preferably the one under which it will be viewed. When metamerism cannot be tolerated, other colorants are selected and tried until the combination does not produce a metameric match. This trial and error method can be very time consuming and is outmoded by methods using color measuring instruments and computer color matching (CCM) systems.

## 5.3 COLOR MEASUREMENT EQUIPMENT

Intelligent use of color-measurement instruments will increase the efficiency of matching colors. They measure color difference in terms that allow description of hue, saturation, and lightness, and also quantify these differences. This makes it possible to estimate the amount of colorant to add to correct the color.

Colorimeters measure color in terms of three numbers called tristimulus values—$X$, $Y$, and $Z$. These values are the amounts of three primary colors—red ($X$), green ($Y$), and blue ($Z$)—needed to match or specify a color under illuminating and viewing conditions as standardized by the ICI. Each color has its own tristimulus values, and identical values are identical colors. Differences in tristimulus values between colors can be analyzed to determine the direction and magnitude of the color difference.

To facilitate the translation of the color difference from numbers to the more meaningful visual descriptive terms and quantify color difference, the $XYZ$ values are converted into the Hunter $L$, $a$, $b$ Scale. This transformation is simple, and all modern instruments offer it as an option. $L$ is lightness–darkness, $a$ is redness–greenness, and $b$ is yellowish–bluish. If the difference between the trial values and given color in $L$, $a$, $b$ values was $-0.5$, $-0.5$, and $+0.5$ respectively, the trial values indicate that the color is darker, greener, and yellower than the given color. If the color difference is unacceptable, then the trial must be corrected by adding white to make it lighter, adding the bluest colorant to make it bluer or less yellow, and adding the reddest colorant to make it redder or less green.

By keeping records of the readings and the addition of the colorants, it is possible to estimate the amounts of the colorants for a correction. For example, one pound of blue lowered $b$ from $+0.5$ to $+0.25$. The goal is to minimize $b$. Therefore, if one pound of blue changed $b$ by 0.25 units, then another pound of blue would lower $b$ to 0. The other colorants are estimated similarly.

Some instruments indicate color difference in the tristimulus values. The color difference is in terms of $XYZ$ ratios, expressed as percent between the values of the batch and the standard. $XYZ$ ratios of 100, 100, 100 indicate that the values of the standard and the batch are the same and the colors match. Any values other than 100 indicate that a color difference exists. It is much more difficult to translate these values into visual descriptive terms as opposed to $L, a, b$ values.

As an example, green reads 101.5, 100.5, 100.5. The *Y* ratio, which is a measure of lightness, is greater than 100 indicating the batch is lighter. In order to determine the hue and saturation difference, it is necessary to compare the relative values of *XYZ* ratios. The hue of a green can only be yellower or bluer so the *Z* ratio is the hue indicator. However, it must be compared to the *X* ratio that is the saturation indicator for a green. In the example, *Z* is lower than *X* meaning that the batch is yellower. For saturation, the *X* ratio must be compared to the *Y* ratio and since the *X* ratio is greater than the *Y* ratio, the batch is less saturated or grayer. Another way of looking at this is that there is more red than needed. Red is the complementary color of green. Complimentary colors when mixed produce gray. The logic is similar for analyzing the remaining category of colors blue, yellow, and red.

*XYZ* values are the basic measurement of color, and for this reason estimating a correction to a batch is easier and more reliable than other color scales but still requires experience. A green reads 110, 110, 110 and is made with white, blue, yellow, and black. An addition based on experience of one pound of blue, one pound of yellow, and 0.1 pound of black is made. The result of the addition was 105, 104, 105 and another addition is necessary to correct the match. To estimate the amount of blue, the ratio affected the most is used to compute the addition.

Although this can be determined experimentally by adding some blue by itself and seeing which ratio has changed the most, it is more expedient to use the following rule. The bluest colorant will lower the *X* the fastest, the reddest colorant the *Y*, and the yellowest the *Z*. Therefore, *X* will be used to estimate the amount of blue, *Y* the black, and *Z* the yellow. One pound of blue lowered the *X* ratio by 5 and to get 100, another pound is added. A pound of yellow will lower the *Z* by 5 so another pound of yellow is needed. The black lowered *Y* by 6, so 0.06 pounds more is needed.

This method works very well, but experience is needed for the first addition and all colorants must be added simultaneously or too much of the colorants will be estimated. Once a batch is shaded using this method, and the readings and colorant additions are recorded, the information can be used for succeeding batches. This has been called the "historical" method and has proven to be very successful.

This method would not have been possible without color measurement. The most difficult decision to make when matching a color is deciding when to stop.

Viewing colors that differ and judging whether or not it is a close enough match is very subjective. No two people see color alike. It is a rare occasion when total agreement will occur, and this is especially true when colors are metameric. Every individual has his or her own idea as to what is an acceptable match, and this may change from day to day because of deadlines imposed to get the job done. This is where instruments perform well. Measurements are objective and consistent and not influenced by external pressures.

### 5.3.1 COLOR DIFFERENCE EQUATIONS

Quantification or color difference makes it possible to establish a meaningful measurement of the closeness of a color match. The basic unit is a just noticeable difference (JND). One JND is a very close match whereas three would be easily perceptible.

Color difference equations calculate the color difference in units of $E$, the error of the color match.

### 5.3.2 TRISTIMULUS FILTER COLORIMETERS

The Hunterlab D25 and the Gardner XL 805 are useful for color correction (shading) and quality control, where the colorants are known and there is no metamerism of any sort. The tristimulus data they provide is for only one illuminant (usually C), and therefore, metamerism cannot be identified or checked.

### 5.3.3 SPECTROCOLORIMETERS

Sherwin Williams Macbeth MS2020/TRS-80 system, Spectroard, Macbeth MC 1500, and Applied Color System (ACS), Spectro Sensor compute $XYZ$ values from the spectrophotometric curve of the color, making it possible to get tristimulus values for any and all of the *Commission Internationale de L'Eclairage* (CIE) standard illuminants, including CWF. Metamerism is detected by measuring $E$ of the samples under the various illuminants. If the FMC2 E is 1.0 for D65 and 2.0 for A, there is metamerism, because the color difference is not the same. Visual evaluation should confirm it.

When a nonmetameric match is needed, the trial and error method of selection of the proper colorants is very inefficient compared to spectrophotometric curve analysis. The spectrophotometric curve of a color is a plot of reflectance of light at each wavelength of the visible spectrum. It is the primary physical measurement of a color and is often referred to as the fingerprint of a color, because identical curves are identical colors and nonmetameric.

The instrument that gives spectrophotometric curves is called a spectrophotometer. Spectrocolorimeters are spectrophotometers and when equipped with a plotter, will provide spectral reflectance curves that are used to identify colorants.

Each colorant has its own characteristic spectral curve that remains identifiable in a mixture, making it possible to ascertain the colorants in an unknown. The colorants are identified by comparing the absorption maximum (reflectance minimum) of the curves of the known to that of the unknown, a method that is only as good as the library of known. If the unknown contains a colorant for which there is no curve, then it cannot be determined. This method easily outperforms experienced visual trial and error. It can readily discern the difference between a red and a green shade phthalo blue pigment, which is difficult by visual means.

There are times when a colorant cannot be determined, because the concentration is very low, or the difference between the curves is insufficient to identify the colorant with any degree of certainty. In these cases, a trial match is made and the spectral curve compared to the unknown. It will be obvious if the wrong colorant was selected. This trial and error method is continued until the curve indicates the proper colorants have been chosen.

### 5.3.4 COMPUTERIZED COLOR MATCHING

CCM is the best tool for matching colors. In the hands of a skilled color matcher, the quality of matches and gain in efficiency can be quite dramatic. It is a big improvement over visual trial and error and the instrumental methods mentioned previously.

CCM systems are available from Diano, Macbeth, ACS, Universal Color Systems, X-Rite, and Instrumental Color Systems. All are good and all have advantages and disadvantages as far as user friendliness is concerned. None of them will do exactly what you would like them to do, but this is true of any software that is not custom designed. Several companies, DuPont, Sherwin-Williams, PPG, and Benjamin Moore, to name a few, have developed proprietary software to satisfy their own needs.

Color matching is a science that is best left to formulators and quality control experts. For the applicator, it can be expressed in more general terms. There are many pigments that can be used to obtain a color. All these pigments vary from one another within the same color group. For example, there are red pigments with yellow cast, orange cast, blue cast, and so forth. The pigments can be clean, meaning that they reflect light in a very limited wavelength range, or they can be dirty and reflect light in a much wider wavelength range.

Pigments are not pure compounds and many are naturally occurring compounds. This means they can vary from one production lot to another. What this all means is that the color will vary slightly from one batch of paint to another, but fortunately the human eye cannot detect very slight differences. For most applications, a $\Delta E$ of 0.5–1.0 is an acceptable color match.

It is important to have a color standard program for consistent color match from one batch of paint to another within established limits. The company that will use the material and the manufacturer of the paint must agree on a color standard that is practical and reproducible in a paint production facility. This is necessary to maintain color consistency and reduce manufacturing errors. Consider, for example, that a paint color cannot be exactly duplicated with a printed catalog color. Similarly, some lead-bearing pigmented material cannot be nonmetamerically duplicated with lead-free pigmented material.

For a new color, the paint supplier should be consulted to see if the color is feasible. They can usually determine how easy it will formulate a color match. If a color standard is already available, the paint supplier can match the established standard and submit a sample. When the sample is approved a master standard is prepared. The painted panels can be used as the master standard and working standard. Color tolerance charts can be prepared to monitor differences.

Since color standards change with time and use, the Macbeth color program ensures a consistent standard. They can also generate color tolerance charts that establish a range of color variation that is acceptable for production color matching and establish the visible limits of an acceptable color match.

If colorimetric instrumentation is used for color matching, the applicator and the manufacturer must use the same programs for color measurement (e.g., Friele, MacAdam, Chickering [FMC] II or LAB) and both machines must agree with one another. An accepted color variation should be established from one batch to another, since there is usually batch-to-batch variation. In general, using an FMC II program, a $\Delta E$ of less than 1.0 is acceptable for a production batch.

For visible color match system, the following parameters should be included in color control:

1. Light source to be used for viewing, that is, daylight or CWF. By using only one light source one can eliminate metamerism from one light source to another. The light should be the one that the product will normally be seen in.
2. Angle at which panels will be viewed.
3. Viewing distance from panel. At 50 ft, all colors look good. At 6 in, color matches are very difficult.

Remember, when comparing colors, that the appearance of the panels must be the same, that is, both smooth or both textured. In addition, the gloss should be the same within limits, generally ±5 gloss units.

## 5.4 COLOR GLOSSARY

- *Appearance*—the way an object looks. It involves not only color but also other visual attributes such as gloss and texture.
- *Color*—a visual response to light consisting of three variables; hue, saturation, and lightness. The most important appearance attribute of an object.
- *Color difference*—magnitude and character of the difference between two colors.
- *Color tolerance*—limit of color difference from a standard that is acceptable. It is generally expressed in terms of a particular color difference equation.
- *CIE LAB of* $L * a * b * E$—the color difference based upon the 1976 CIE color difference equation. One CIE LAB E is approximately 2 JND units of color difference.
- $\Delta L$—designates lightness differences.
- $\Delta a$—designates redness–greenness.
- $\Delta b$—designates yellowness–blueness.
- $\Delta E$—a unit of color difference. It constitutes the total differences in hue, the differences in saturation, and the differences in lightness.
- *FMC2 E*—the color difference based upon the Friele, MacAdam, Chickering color difference equation. One FMC2 E is approximately 1 JND unit of color difference.
- *Gloss*—subjective term used to describe the relative amount and nature of mirror-like (speculate) reflection. Different types of gloss are frequently arbitrarily differentiated, such as sheen, distinction-of-image gloss, and so forth. Trade practice recognizes the following stages, in increasing

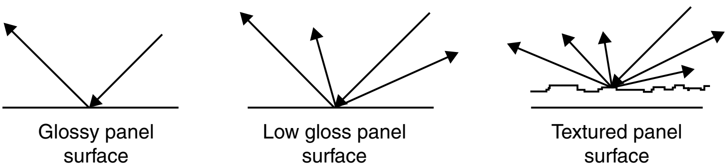


**FIGURE 5.1** Geometric metamerism.

order on gloss; flat (or matte)—practically free from sheen, even when viewed from oblique angles (usually less than 15 on 85 degree meter); egg-shell—usually 20–35 on 60 degree meter; semi-gloss—usually 35–70 on 60 degree meter; full-gloss—smooth and almost mirror-like surface when viewed from all angles, usually above 70 on 60 degree meter.

- *Geometric metamerism*—phenomenon exhibited by a pair of colors that appear to be a color match at one angle of illumination and viewing but which are no longer a match when the angle of illumination or viewing is changed, caused by gloss and/or texture differences (see Figure 5.1).
- *Hunter Lab E*—the color difference based upon Hunter's color difference equation. One Hunter Lab E is approximately 3 JND units of color difference.
- *Metamerism*—when two or more samples match under one set of viewing conditions (kind of light source and angle of view) for an observer, but do not match under a different set of viewing conditions for the same observer. Those samples may not match for a different observer under either viewing condition.
- *Master color standard*—the absolute reference color standard; a color standard panel to which all standards of a given color are compared.
- *Primary working color standard*—a color standard that is compared to painted items (usually) such as paint test panels and finished goods. It is used to color check everything, where the Master Standard is used only to check color standards and settle color disputes.
- *Secondary working color standard*—a back-up to the primary working color standard. It becomes the primary working standard when the original primary working color standard is determined to be unusable.
- *Texture*—nonuniform surface. Like gloss, texture affects the appearance of color.

The visual evaluation of a color match is a very subjective human judgment. If the nature of the process is not fully understood and appreciated, poor color control will result, or much more time than that is necessary will be spent in getting acceptable matches.

## 5.5 COLOR STANDARDS AND METAMERISM

The color standard is the most important part of a color control program. Whether the color is controlled by visual observation, color measurement, or a combination of both, it is important that the color standard and the product are not metameric to one another.

Metamerism is when colors match under certain viewing conditions and mismatch when the conditions are changed. The various viewing conditions that can cause metamerism are

- The type of light source
- The angle of illumination and angle of view
- The human observer

Metamerism can occur with all three conditions. Classification of the metamerism depends on the source.

1. *Light source metamerism*—colors will match under one light source (daylight) but do not match under another (incandescent).

   *Cause*: colorants different than those in the color being matched were used.

   *Solution*: use the same colorants.

2. *Geometric metamerism*—colors will match at only one angle of illumination and viewing. For example, samples will match when they are oriented so that they are illuminated at a 0° angle to the surface and viewed at the 45° angle, but will be mismatched when the viewing angle is changed to 75°.

   *Cause*: the gloss and/or texture is different.

   *Solution*: control gloss and/or texture.

3. *Observer metamerism*—colors will be a match by one observer but not by another.

   *Cause*: individuals have different color visions, and it becomes evident when light source metamerism exists.

   *Solution*: eliminate light source metamerism.

# 6 Liquid Paint Application Systems

Liquid paint can be applied in many different ways. The three major components of a paint line are pretreatment, application, and cure. The type of industrial application process will be determined by the product, the volume, the quality requirements, and other factors. It may be as simple as a dip tank and a method of hanging parts, or it may be a fully enclosed automated system that allows continuous pretreatment, application, and curing. A basic conveyorized paint line layout is illustrated in Figure 6.1.

The actual layout and specific equipment vary widely, but all paint lines have the same general stages: a loading area, pretreatment or cleaning stage, application stage, curing stage, and unloading area.

The loading/unloading stages are where parts are put on and taken off the paint line. The pretreatment stage is where the parts are prepared for the coating application stage. Cleaning can be done mechanically, such as blasting, or chemically by solvent washing, solvent wiping, power washing, or dipping. After cleaning, the parts are dried by heat or forced air or a combination of the two so that they are ready to be painted.

Paint can be applied by spray method using conventional handheld spray guns, high-volume-low-pressure (HVLP) guns, automatic guns, automatic rotary bells, or disks. The spray equipment can be either nonelectrostatic or electrostatic. Dip systems, flow coaters, curtain coating, or roll coating are other application methods.

The curing stage is where the paint film is formed. Paints can be cured by air drying or heating. Ovens for heating are conventional gas-fired, high air velocity gas-fired, electric, infra red, UV energy, electron beam, or induction. The ovens can be

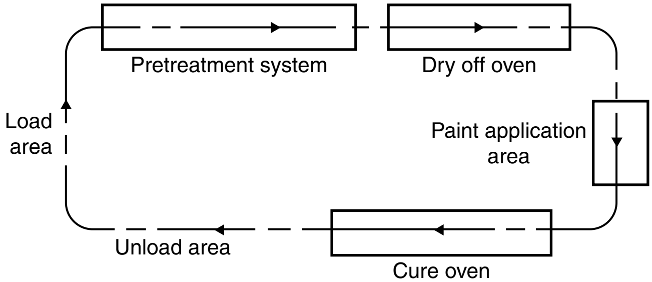


**FIGURE 6.1** Basic paint system layout.

either batch type or continuous. Parts are moved from one stage to another by manual or automated conveyor systems.

## 6.1 PART PREPARATION

As discussed in Chapter 1 on pretreatment, a properly prepared surface is critical to the success of the coating. Paint does not hide defects or clean a substrate. If the substrate is dirty or has a film on it, the paint will adhere to the dirt film, since it is the first surface it comes in contact with. If that film adheres poorly to the substrate, then the paint will lift off.

In many cases, the dirt or film may not be compatible with the paint. This will cause the paint to pull away from that area and cause fish eyes or crawling on the surface of the substrate. With the need to use high-solids, solvent-based paints, or water-based paints, the cleaning step becomes more critical. Prior to the regulation of organic solvent emissions, paints were commonly 20–30% solids—the remainder being solvent. In many cases, this excess of solvent could attack the surface film and allow the paint to adhere through it to the substrate. Today this is not the case.

With regard to surface defects such as scratches, welding marks, porosity, and so forth paint will only flow over a surface in a uniform manner and will not hide a defect as shown in Figure 6.2. The only way to hide the defect at this point is to sand the paint until smooth and then recoat.

Surfaces to be painted must be clean and dry to ensure paint adhesion. They must also be nearly as smooth as the desired final finish. Generally, paint cannot be used to hide surface defects. Paint will often highlight surface defects by reflection and make them more noticeable.

In addition to cleaning and smoothing, surfaces are often converted to a material different from the original before painting. Phosphated steel and flamed plastic surfaces are examples. Surface conversion is generally used to improve paint adhesion, reduce corrosion, or both.

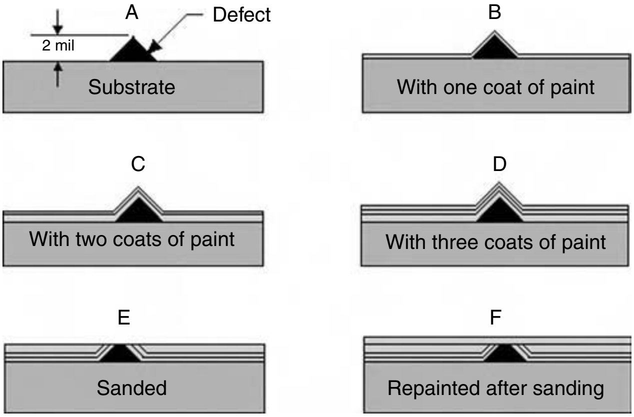


**FIGURE 6.2** Repair of a paint defect caused by particulate on the surface.

### 6.1.1 SMOOTHING

Some surfaces require grinding, filing, or sanding to make them smoother before the paint is applied. Grit blasting or heavy grinding can be used to remove burrs or scale. In some cases, the substrate will require a combination of these processes. Large pits, holes, seams, or scratches in a surface can be filled with a liquid or paste material and then sanded after they harden.

Typical grinding papers use aluminum oxide or silicon carbide (carborundum) abrasives. Blasting abrasives may be sand, glass, metal grit, or walnut hulls. These media are available in a variety of grit sizes. Abrasives must be replaced or cleaned regularly so that they do not become oily and contaminate the surface.

## 6.2 SPRAY APPLICATION OF PAINT

Paint can be applied to a substrate in many different ways. Each method has advantages and limitations. The needs of the product and the manufacturing process will help determine the correct application method. An understanding of the different application processes is necessary in order to evaluate them for a specific task.

Most industrial paint systems apply liquid coatings with spray equipment. The liquid coating is delivered from a container to a spray device that uses pressure to break the liquid stream into fine droplets. The even distribution of the liquid paint into a finely divided mist of droplets is called atomization. There are several different types of spray guns and different methods of atomization and pattern control that can be used to control quality and efficiency.

### 6.2.1 METHODS OF ATOMIZATION

- Air-spray is one of the earliest methods of atomization. An air-spray device mixes a high-velocity air stream with a low-velocity fluid stream and the resulting friction creates the paint droplets.
- Hydraulic atomization occurs when a high-velocity fluid sheet that is formed by a small orifice at the spray gun tip exits into a stationary atmosphere. The resulting friction causes atomization into droplets.
- Centrifugal atomization occurs when a fluid stream is introduced at the back of a disk that is rotating at high speed. The centrifugal force of the rotating disk delivers the paint to the edge of the disk and breaks it into a fine mist.

There are certain features that all spray applicators have in common, but each different spray device has particular differences that make it fit with a certain application. An understanding of the different applicators and their strengths is useful in the selection of the correct device for a particular application.

### 6.2.2 MANUAL SPRAY GUNS

There are a number of different spray gun technologies used for manual spray application of industrial coatings. Most coating systems use manual spray guns, alone or as reinforcement for automated application. Manual spray equipment provides the freedom to spray in hard to reach areas at different angles that would be difficult to reach with a stationary automatic gun.

Manual spray technology is available with or without electrostatic capability for better transfer efficiency. Handheld spray guns are typically identified by the following names:

- Conventional air-spray
- HVLP
- Airless
- Air-assisted airless (AAA)
- Electrostatic HVLP
- Electrostatic air-spray
- Electrostatic AAA

Each of these devices has features that make it work well in a given situation. Selection often depends on the cost of the device, the coating(s) to be used, and the difference in application efficiency. Other factors may also influence the specific gun used in a certain application.

### 6.2.3 AUTOMATIC SPRAY EQUIPMENT

Automatic spray equipment is used when the volume of work exceeds the capabilities of manual operators, the product is too large for men to reach, there is an interest in reduced labor, or there is an interest in automation for more precision. It is available in all standard forms of air atomization and also uses centrifugal or rotary devices for atomization.

Most automatic spray systems use a device that moves the spray guns and controls application. Programmable logic controllers (PLCs) use part recognition systems to trigger guns on, initiate color change, and adjust the equipment for optimum efficiency. In addition to control of paint application, PLCs are used for paint mixing, color changes, and other control tasks.

### 6.2.4 SPRAY SYSTEMS

Conventional air-spray guns are common spray tools that can be used with and without electrostatics. A conventional air-spray gun is a precision tool that uses energy in the form of compressed air to atomize the material. Air and paint enter the gun at different points and meet at the head of the gun. The high-velocity air stream from the annular hole around the nozzle passes the low-velocity fluid stream and the resulting friction creates a pattern of fine droplets. The pattern of fine paint particles provides a uniform thin film of coating on the part surface.

When the gun trigger is pulled back slightly, an air valve, usually located in the upper portion of the handle, will open and allow air only to reach the gun tip. When the trigger is pulled back further, the fluid needle is retracted and paint begins to flow from the fluid nozzle. Immediately upon leaving the nozzle, it is mixed with air from

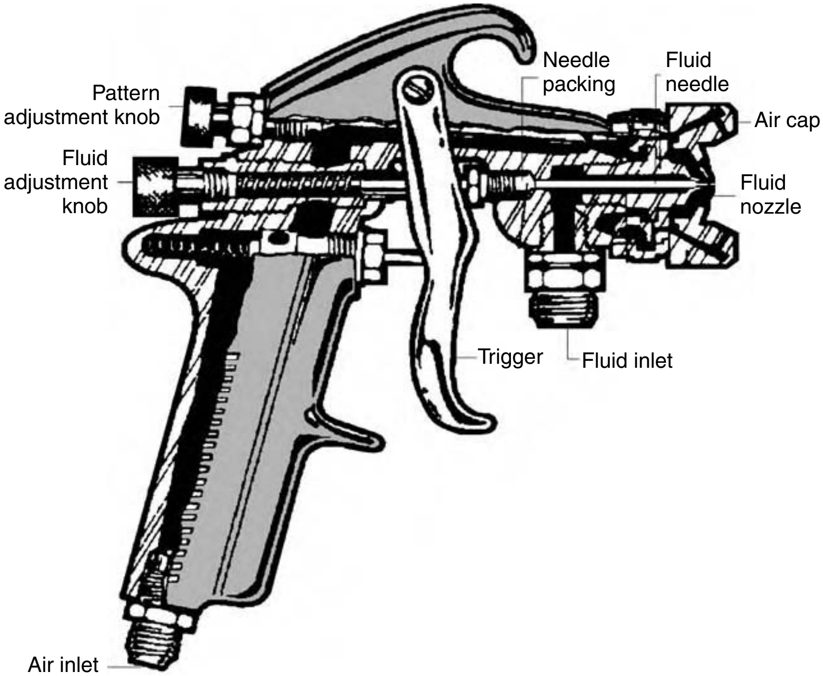


**FIGURE 6.3** Spray gun components.

the air nozzle, and the spray pattern is formed. Figure 6.3 shows the inside of a typical air-spray gun.

### 6.2.4.1 Suction or Siphon Systems

A suction or siphon feed gun uses a stream of compressed air to create a vacuum, allowing atmospheric pressure to force the fluid material from an attached container to the spray head. A siphon cup is a simple system for testing, for very short runs, for shading operations, or similar situations that require a small amount of paint and a short run. These systems typically use a one-quart container, and they are not very effective for high-viscosity materials. A siphon cup system is shown in Figure 6.4.

Another system that works well for small volume applications uses gravity to feed the paint to the gun tip. It is lightweight and uses virtually every drop of paint in the cup so that almost no paint is wasted in the cup. A gravity cup is shown in Figure 6.5.

### 6.2.4.2 Pressure Feed Systems

A pressure feed system applies paint that has been forced to the gun by pressure, either from compressed air or a pump. Pressure-feed systems are used in situations requiring more volume, delivered from a larger vessel, rather than the small cups used in gravity and siphon systems. It is also suitable for paints with higher viscosity.

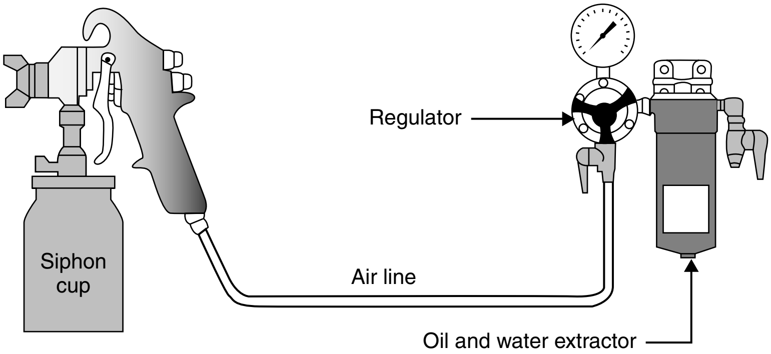


**FIGURE 6.4** Siphon feed system.

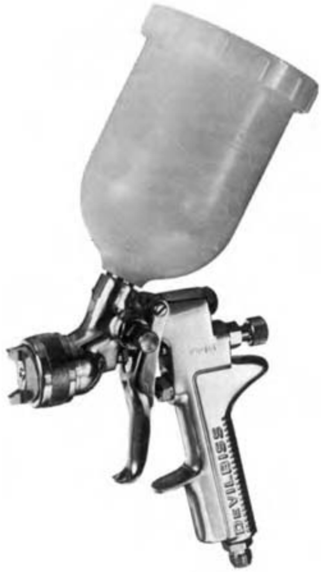


**FIGURE 6.5** Gravity feed system.

Pressure pots use compressed air to create fluid pressure and force the paint through the fluid hose to the spray gun. There are many sizes of pressure vessels that can be used depending on the size of the operation. Five-gallon pots are fairly common. A system with a 5-gal pot is shown in Figure 6.6. A pump is often used to supply coating material from a larger container such as a 55-gal drum.

### 6.2.4.3 Circulating Systems

Some systems deliver paint to the booth but do not circulate it back to the container. Circulation systems are more effective for maintaining a stable paint material and limiting waste materials.

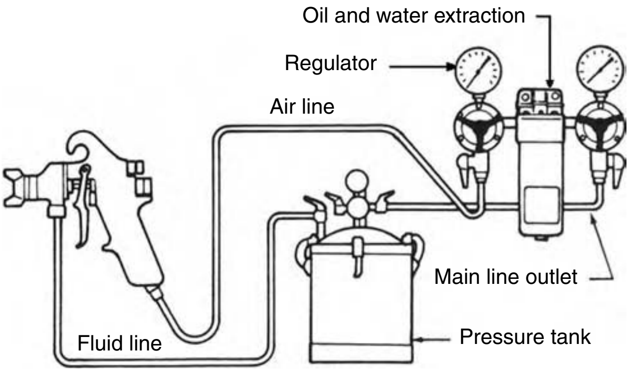

Oil and water extraction
Regulator
Air line
Main line outlet
Pressure tank
Fluid line

FIGURE 6.6 Air-spray pressure feed system.

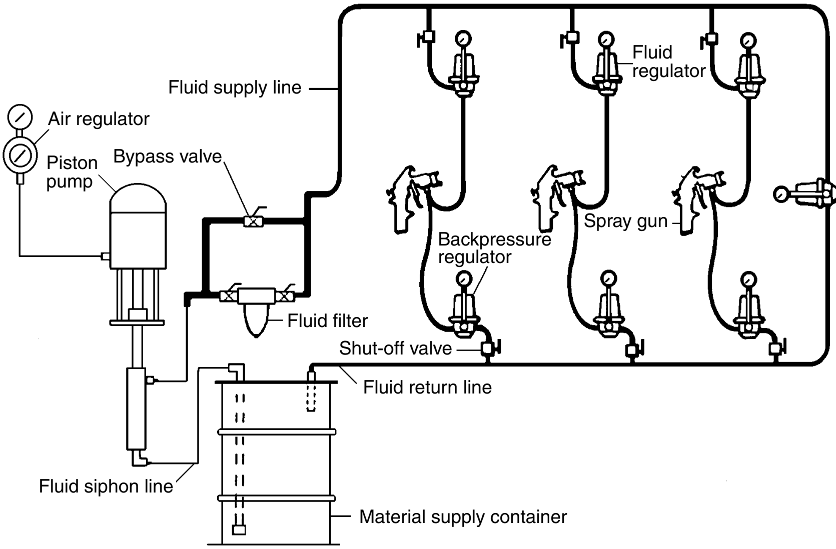

Fluid supply line
Air regulator
Piston pump
Bypass valve
Fluid regulator
70 lbs.
20 lbs.
Spray gun
Backpressure regulator
Fluid filter
Shut-off valve
Fluid return line
Fluid siphon line
Material supply container

FIGURE 6.7 Paint circulation system.

Many paint lines are installed with paint supply systems that bring fluid to the booth and circulate it back to a supply container in a "paint kitchen." A typical circulating system is shown in Figure 6.7.

Circulation systems have several advantages over pressure tanks. The material volume is not limited to the pressure pot size. Material is supplied directly from the container it was shipped in or a large tote. If a container is running low, a new one can be attached without any lose of production time.

There is very little waste with a circulating line. The material in the hose from the color manifold to the applicator is usually a very small volume, often as low as 6–8 oz of material. A circulation line is only useful when the paint can be consumed in a reasonable period. If it is circulated through the system for more than a week without any consumption, the material may become unstable and create appearance and performance problems.

Circulating systems often use a manifold of independent valves for different colors and supply of solvent and compressed air. Automatic color changers are often used to speed up color change and minimize wasted paint. These systems usually have different valve arrangements that facilitate efficient color change options. The valves are normally closed and interlocked to prevent any flow of material into the manifold or other color valves. The color valves open in sequence to shut off the color in use, purge the system using solvent and air, and introduce the fresh color.

The supply containers are often located in an isolated room and material is pumped to the booth or series of booths through a hard pipe system. These rooms are often called paint kitchens, red label rooms, or paint lockers. They contain any number of containers depending on the number of colors required. Each system has an independent pump, material agitator, pump surge chamber, paint filters, backpressure regulator, and other components of a circulation line. They can provide material to one or more spray stations at the same time in addition to providing good material circulation while the specific color is not being sprayed.

Circulation systems route the paint to the booth and circulate it back to the container. Regulators are used to control the flow and make sure that the material maintains pressure and does not settle or separate in the line.

Systems that use a paint kitchen with multiple colors could have a two pipe circulating system similar to the one shown below. A regulated flow of material is supplied to each station from a central location. The supply line passes through the spray station and returns to the drum to close the loop. Circulation of paint in this way provides a consistent flow and homogenous blend of paint. It reduces the labor of mixing and transporting pots and improves control of the process. However, this type of system has many components to maintain and has greater potential for material degradation.

Some circulation systems use graduated pipe designs. The graduated pipe system is typically used in automotive final assembly and tier-one finishing plants where material flow; pressure and velocity consistency are most important. The graduated pipe system uses the material viscosity and pipe and hose diameters to create the system back-pressure and material flow. The system typically incorporates a pump, high-flow surge chamber, filter housing, and back-pressure regulator. The only adjustments are the pump output pressures and material return pressures to the paint kitchen.

Pig-able systems are fast becoming the choice of design for frequent color changes where material recovery and reduced solvent usage are imperative.

The pig-able system incorporates special color valves that allow for cleaning (pigging) as part of the circulation system. While traditional circulation lines are difficult and costly to color-change, a pig-able line can be color-changed fairly quickly and inexpensively. When a line is color-changed a small diameter plug, referred to as a "pig," is passed through the fluid delivery line to clean out any paint solids that are still present after a solvent/air purge.

The typical pig-able paint system allows faster color-changes, recovery of more material, and reduced solvent usage during flushing. A pig-able type system can provide large cost savings for users responsible for numerous colors.

The traditional approach to paint circulation line design did not provide simple or fast color change. In order to color-change them, the user had to flush main circulating lines or provide booth mounted mini systems. The waste material to flush this type of system could include 2+ gallons of paint and 30+ gallons of solvent per flush. The return on investment by utilizing pig-able technology is generally 6 months or less and provides a more flexible material-friendly circulating system.

#### 6.2.4.4 Plural Component Mixing Equipment

Two component materials must be mixed prior to spray application. Mixing can be as simple as mixing the two materials at the desired ratio into a siphon cup or pressure feed tank in an appropriate batch size. For high-volume mixing requirements a mechanical proportioner, gear driven mixer, or an electronic mixer may be the better choice. In all cases, the objective is to consistently mix two or sometimes three materials at the recommended mix ratio while always generating little or no waste. Mix ratios may range from 1:1 to 50:1 or greater. It all depends on the coating and the application requirements.

Mechanical proportioners are typically one or two pumps that are mechanically connected together in either a fixed ratio or variable ratio configuration. A fixed ratio pump system with a 1:1 ratio has one pump air motor with two identical pump-lowers that deliver the same volume of material when the pump is actuated. Fixed ratio systems are available in many sizes and the pumps are sized to produce the particular ratio needed. A variable ratio system has one pump to deliver the resin material with an adjustable arm that actuates a smaller catalyst pump at the desired cycle rate to deliver the correct material mix ratio.

Mechanical systems, like the dual piston pump system shown in Figure 6.8, cost less money than the cost of more sophisticated systems, but they are maintenance prone and flushing is difficult and expensive. Ratio is adjusted by move the fulcrum position by trial and error.

A gear-driven system uses a PLC or PC to control the speed of each pump to establish a mix ratio. The gear driven system requires a low-pressure material delivery source to supply the two different gear pumps, then the gear pumps supply the desired output and ratios to the spray gun.

There is typically one system for each spray booth and spray application. These systems can be more complex with the amount of components required, but they are accurate, flexible, and can consistently deliver very low material flow rates with less concern for mix ratio variances.

Some gear-driven systems use two gear pumps on a common drive. Some gear systems use independent motors for the two gear pumps. Mix accuracy depends on the speed of the drive motor. These systems are sensitive to the coating viscosity, and they do not provide verification of mix accuracy.

The electronic mixer requires a separate material delivery source that could be as simple as two pressure tanks to a large circulation system. The electronic mixer has a

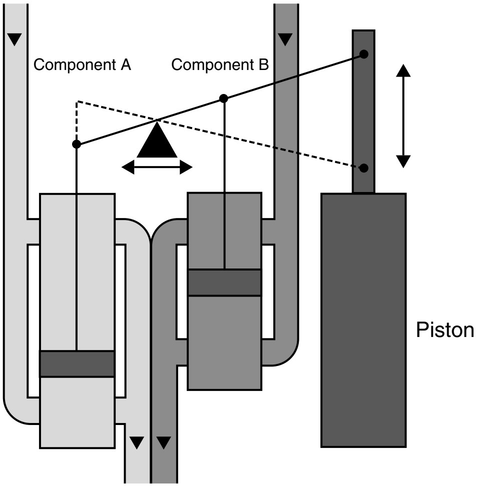


**FIGURE 6.8** Dual piston pump mixing system.

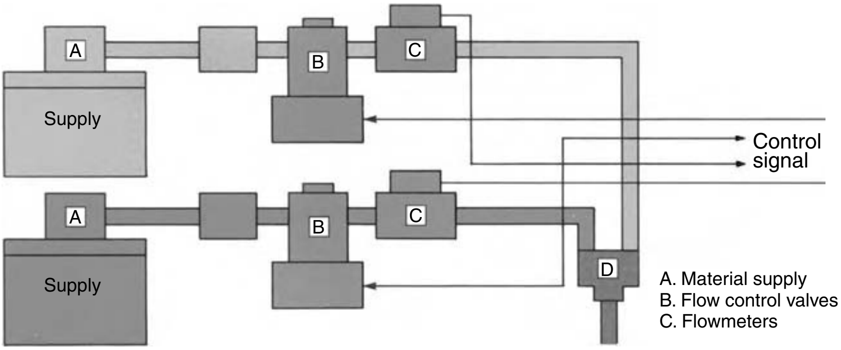


**FIGURE 6.9** Two component proportioning system.

back plate that may be mounted outside the booth, inside the booth if hazardous rated, or mounted directly on the gun mover or robot. It typically includes an A and B material flow meter, fluid flow regulators, and a mix manifold and static mixer. These systems can be used on one spray booth with one spray gun or can be networked together with other systems in multiple spray booths. It is recommended that one back plate be used with only one applicator.

Electronic systems provide precision mixing and information such as notification if the material supply is low. A well-designed system can supply reliable mix ratios and provide alarm conditions so that problems are quickly identified and corrected. A typical system is shown in Figure 6.9.

The right proportioner is dependent on the application, material, and production speed.

Electronic mixers use a small PLC to control the mix ratios and often the material delivery rates. These systems are very flexible, have a wide range of mix ratio options, provide documentation for environmental reporting, and are very consistent. Many electronic mixers use a PC, which is more flexible and allows a windows format for ease of control.

### 6.2.4.5 Air Nozzles

The air nozzle directs the flow of compressed air through a series of holes into the paint stream at the gun tip. The air atomizes the paint and directs the flow of atomized paint into the pattern. A profile is shown in Figure 6.10 with fluid flowing around the fluid needle and air introduced by the air horns at the gun tip. Figure 6.11 shows the air nozzle.

Some air nozzles are referred to as internal-mix. With an internal-mix nozzle, the air and paint are mixed inside the nozzle and the pattern is formed as the mixture exits through a hole in the nozzle tip. An air nozzle introduces the compressed air to the fluid stream at the gun tip.

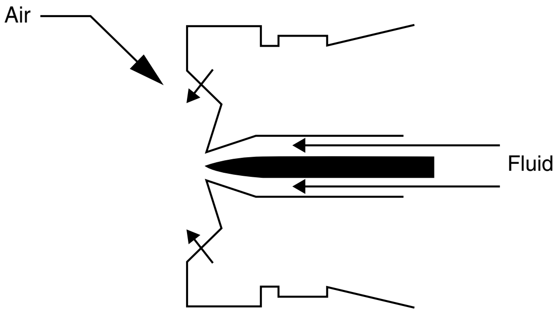


**FIGURE 6.10** Spray gun air nozzle.

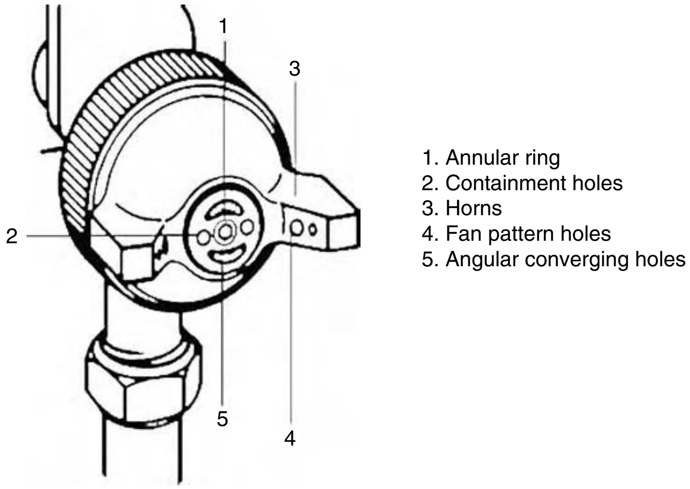

1
3
2
5
4
1. Annular ring
2. Containment holes
3. Horns
4. Fan pattern holes
5. Angular converging holes

**FIGURE 6.11** Air-spray air nozzle.

### 6.2.4.6 Fluid Nozzles

The fluid nozzle and needle combination is used to control the volume of coating material delivered at the spray tip. The fluid needle is pulled back when the gun is triggered and fluid flows through the nozzle. When the trigger is released, the needle slides back into place and shuts off the flow. Atomization occurs at the gun tip when compressed air is directed into the paint stream as it exits the fluid nozzle. The fluid orifice in the nozzle assembly provides the lowest possible velocity fluid stream. A properly sized air cap will provide a high-velocity air stream from the annular holes to provide atomization at the gun tip.

Atomization is measured by micron size and distribution in a given area by a Malvern or similar in-flight particle analyzer. The size of the paint droplets will depend on the particular material being sprayed and may vary widely from a low of around 5 $\mu$m to above 100 $\mu$m. The particle size distribution needed to achieve a particular finish with a particular paint will depend on the product being painted and the film build requirements. Typically, a finer droplet size will provide a smoother finish.

Selection of a particular fluid nozzle depends on the viscosity of the coating material and the required level of atomization. Different sized fluid nozzles are available for materials including paint, adhesives, mastics, flocking materials, and so forth.

Hardened steel fluid nozzles are commonly used for solvent-based paints. For paint materials that are abrasive, the fluid nozzle may be an alloy. Stainless steel is required for water-borne coatings or other corrosive fluids. For materials that are unusually abrasive, the tip can be fitted with a carbide insert. Some plastic fluid nozzles work well due to their low surface friction and their ability to conform to worn fluid needles.

Usually, a nozzle with a smaller orifice will work fine with a lower viscosity material while a higher viscosity material may require a larger nozzle. If the nozzle is too small to deliver the volume of paint needed, the fluid pressure must be increased in order to compensate. Excessive pressure can create application problems so it is important to select the correct nozzle for the material being sprayed.

Nozzle size, fluid flow, and pressures are related. Selection of a fluid nozzle should consider the viscosity of the material, the amount of material required to achieve the desired film thickness, and the maximum desired fluid flow rate.

Table 6.1 shows some examples of different fluid tip orifice sizes and the types of products that they are likely to be used with them.

Materials with high viscosity will flow slower than thinner fluids, usually requiring a larger orifice and higher fluid pressure to achieve the desired fluid flow. Low-viscosity materials flow more readily at lower pressure through smaller orifices.

To determine a fluid flow rate for a specific orifice size, turn off the atomizing air, trigger the gun, and fill a graduated beaker for 30 s. Measure the amount in the container and multiply it with 2 to determine the volume in ounces or cubic centimeters per minute. Record the fluid pressure, material viscosity, and orifice size for reference.

TABLE 6.1
Fluid Tip Orifice Sizes

| Orifice Range | Viscosity Range | Example |
|---|---|---|
| 0.022–0.028 | Very thin | Solvents, stains |
| 0.040–0.052 | Thin | Lacquers, primers |
| 0.059–0.070 | Medium | Varnish, urethanes |
| 0.086–0.110 | Heavy | Epoxies, vinyls |
| 0.125–0.500 | Very heavy | Block fillers |

TABLE 6.2
Delivery in Ounces per Minute at Different Pressures

| Orifice Size | At 8 psi | At 12 psi | At 18 psi |
|---|---|---|---|
| 0.040 | 14 | 18 | 24 |
| 0.046 | 18 | 22 | 30 |
| 0.052 | 22 | 28 | 36 |
| 0.059 | 31 | 36 | 48 |
| 0.070 | 40 | 48 | 60 |

Table 6.2 shows the difference in fluid flow at different pressures for a material with a viscosity of 21 s in a #2 Zahn viscosity cup.

Control of fluid flow can be adjusted by changing the fluid nozzle, by turning the fluid adjustment knob located on the rear of the gun handle, or by changing the air pressure through the fluid regulator.

The fluid control knob on the gun is provided so that the gun can be adjusted when used with a siphon feed system. A pressure feed system should typically be adjusted by air pressure regulation with the fluid control knob left in the full-open position. Fluid control by adjustment of the needle position is not recommended.

Triggering a spray gun with no atomizing air can be useful for setting the proper fluid pressure. The resulting paint stream should flow in a solid stream for approximately 1′0″ to 2′0″ before falling off. Anything in excess of 2 ft indicates that the fluid pressure is too high.

### 6.2.4.7 Proper Fluid Pressure

The fluid needle fits into the orifice of the fluid nozzle. When the gun trigger is pulled, the fluid needle is pulled back from the orifice and paint material is allowed to flow from the gun. When the trigger is released, the fluid needle moves forward and stops fluid flow.

Fluid needles are machined from hardened steel or stainless steel with a tapered end. Fluid needles are also made of engineered plastics. The tapered end is designed to match the orifice of a family of fluid nozzles.

The fluid nozzle and needle is a pair. If a needle does not match a particular fluid nozzle, the taper will not match and fluid will leak from the nozzle tip, the gun will spit and drip. The nozzle and needle should be replaced. The manufacturers catalog will list the correct needle and nozzle families.

Sometimes it is necessary to make a needle adjustment to compensate for wear. Every time the gun is triggered, the needle slides back across the inner surface of the fluid nozzle and causes a small amount of wear. Eventually, there is enough wear to create a gap between the needle and the seat of the orifice and the gun will leak.

## 6.3 AIRLESS SPRAY GUNS

Airless spray systems use hydraulic pressure to force the fluid through a spray tip or orifice at high pressure. The combination of pressure and orifice size creates a pattern. Orifice sizes are catalogued by flow capacity and degree of spray angle.

An airless spray gun does not use compressed air for atomization, so there is no air nozzle with atomizing ports like those found on an air-spray gun. There is only one trigger position, full open.

An airless system works with a high-pressure pump that delivers fluid to the gun tip at 500–6000 psi and forces the fluid through the orifice.

Airless systems can be used with heaters to reduce the spray viscosity and improve finish quality. The heater helps to control spray viscosity for consistency and may be particularly helpful with thicker materials. Figure 6.12 shows an airless spray system.

### 6.3.1 Fluid Needles and Tips for Airless Systems

Usually an airless needle will be a permanent assembly having a ball, approximately 1/8″ diameter, silver soldered to the end. This ball will “seat” or act as a seal to prevent fluid from leaking through the fluid tip when the gun is not in use.

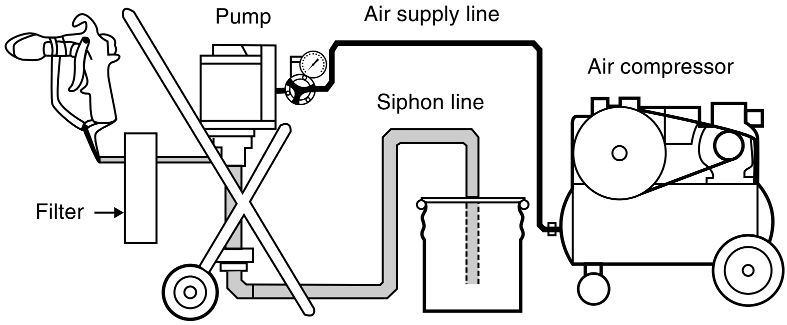


**FIGURE 6.12** Airless spray system.

## TABLE 6.3
## Orifice Sizes for Airless Systems

| Orifice Size | Viscosity Range | Material |
|---|---|---|
| 0.009–0.010 | Very thin | Acetone |
| 0.011–0.013 | Thin | Water |
| 0.015–0.021 | Medium | SAE #10 oil |
| 0.026–0.036 | Heavy | SAE #50 oil |
| 0.043–0.072 | Very heavy | Vaseline |
| 0.072–0.081 | Extra heavy | Mastics |

The reason an airless needle is not smooth and tapered like an air-atomized needle is that the high fluid pressures would unseat a tapered needle and cause a leak.

The ball at the fluid needle tip provides a surface for the fluid to push ball into a seated position at the fluid tip and prevent the needle from lifting or retracting. It is rounded so that when the trigger is pulled, the fluid is deflected and it can retract. If it were flat, you would have to exert considerable force on the trigger to overcome the resistance generated by the high fluid pressure. Typically, there is only one size fluid needle for all tip sizes for an airless gun.

The orifice size in the fluid tip will start around 0.009″ and range upward in excess 0.081″. The larger orifices can handle heavier materials that require higher pressures. Table 6.3 will give a general idea of orifice size for typical materials.

The orifice size and the spray angle will define the pattern size. The pattern size can only be adjusted by changing fluid tips. A fluid tip with the widest possible angle and the smallest orifice size that will work well with a given fluid viscosity will provide a wide area of coverage and controlled film build.

With an air-atomized gun, the operator can adjust the pattern size, alter the atomization, and increase or decrease fluid flow. There is no way to make similar adjustments on an airless gun.

An airless spray gun works like a typical spray nozzle. Atomization is achieved when the fluid is forced through the orifice at high pressure. The orifice will provide a specific pattern size and a specific fluid delivery at a designated pressure.

Airless systems can operate at pressures up to 6000 psi. The systems are manufactured with safety features to protect the operator from the high-pressure discharge. Operators of airless systems need to be careful not to trigger the gun toward any part of their body.

Airless units and all connected components must be grounded to prevent static discharge. Electric units have three-wire grounded plugs, air driven pumps have ground straps, and a proper airless hose has a ground wire built into the jacket of the hose.

Solvent should not be sprayed under pressure through the airless tip and/or diffuser. An explosion or fire could result from static buildup in the presence of flammable vapors.

Never attempt to remove a hose, gun, or any piece of the system without first releasing the pressure and disabling the pump.

An airless spray gun does not produce the fine atomization required for class A surfaces. It is used primarily in wood finishing, leather tanning, fabricated metal manufacturing, and painting contractor applications. Transfer efficiency can be very good and a lot of fluid can be delivered per minute making the airless system a good device for field applications. An airless spray gun delivers more fluid with less fog than a conventional air-spray gun.

If finer atomization is required, a fine finish tip and the use of a diffuser may help. The diffuser will shear the material by disrupting the fluid flow before it gets to the fluid tip where it is atomized.

## 6.4 AIR-ASSISTED AIRLESS SPRAY GUNS

The AAA gun uses a lower fluid pressure (typically 400–800 psi) with an airless tip and an air nozzle for atomization. This combination of elements provides faster application of material than air atomized spray provides, reduces overspray and rebound, and provides enough forward velocity to penetrate some recesses and cavities. The pressure range used with AAA spray guns is much higher today for high solids and ultra high solids materials. A picture of an AAA gun is shown in Figure 6.13. Note the "duck bills" at the gun tip that provide protection against accidental exposure to the high-pressure spray.

AAA does not provide the fine atomization necessary for extremely high-quality finishes. It is very popular in the wood finishing industry where stains, sealers, fillers, glazes, lacquers, and polyurethane materials are common. It is also very effective for applications that require high-TE, low overspray, fast application, and modest appearance standards.

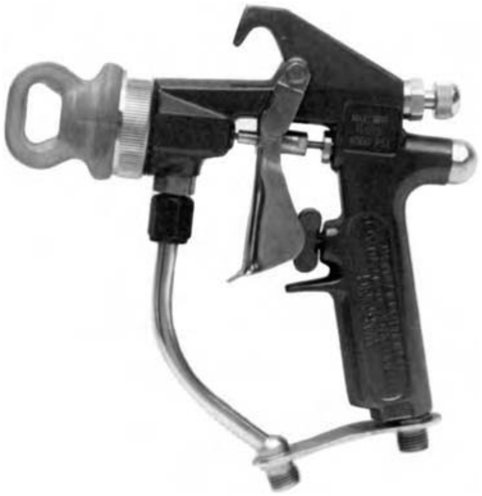


**FIGURE 6.13** Air-assisted airless spray gun.

AAA spray guns are often used in systems with very high line speeds, but they are particularly well suited to systems with slow to medium line speeds and coating materials that are thin to medium in viscosity, a typical maximum of 28–32 s on a #2 Zahn cup. Material is typically delivered with a conventional air driven pump in a range of 10:1 to 30:1 power ratio.

Unlike airless, this type of gun relies heavily on the correct air pressure in relation to fluid pressure. AAA uses an air cap that is similar to the one that would be used with a conventional air-spray gun, but the air is used primarily to distribute the droplets more evenly and to assist the air in remaining stationary in relation to the fluid stream or sheet. The fluid is at a higher pressure in an AAA gun. Primary atomization is still achieved by fluid flow through an orifice. The compressed air helps to create a more uniform pattern, better paint particle distribution, and finer atomization than an airless spray gun.

Airless and AAA systems are often used with heaters to reduce the spray viscosity of materials that are higher in solids.

Airless systems are often used for field painting or shop painting that does not require fine atomization. AAA systems are suitable for a wider variety of applications.

Like an airless system, atomization is achieved by the choice of fluid tips and the pressure used to propel the coating through it. The added feature of compressed air has very little effect on atomization. Its main function is to fill the pattern so that the coating is uniformly deposited on the surface. Figure 6.14 shows a typical AAA system with a heater.

A comparison of the three gun types that have been discussed is outlined in Table 6.4.

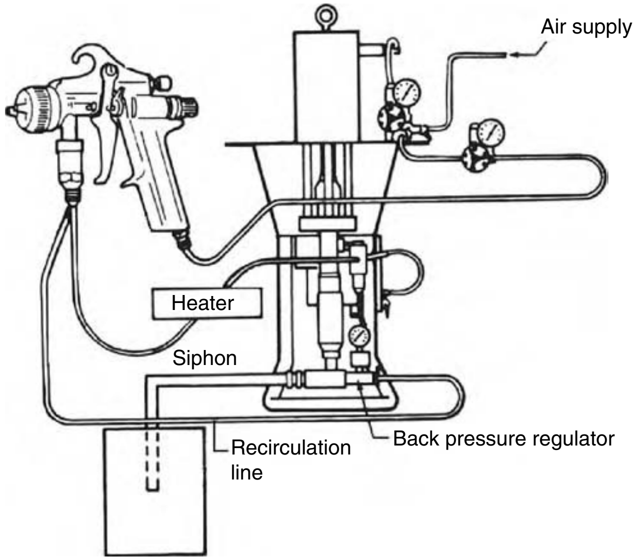


**FIGURE 6.14** Air-assisted airless system with heater.

**TABLE 6.4**
**Comparison of Different Spray Guns**

| | Air Atomized Spray | Airless Spray | Air Assisted Airless |
|---|---|---|---|
| Finish appearance | Excellent | Coarse | Very good |
| Transfer efficiency | Low | Good | Good |
| Fluid flow rates | Very low to medium, usually less than 30 fluid oz/min | High or very high flow rates, over 80 fluid oz/min | Wide range, 7 fluid oz/min to 78 fluid oz/min |
| Booth maintenance | Lot of rebound and overspray, booth maintenance is high | Less rebound and overspray, less maintenance | Least rebound and overspray, maintenance is low |
| Pattern adjustment | Yes | Tip selection | Yes (limited) |
| Tip plugging | Virtually none | Yes | Yes |
| Equipment life | Very long due to very low fluid pressure | Very high fluid pressure, high tip wear and shorter pump life[a] | Less tip wear, lower fluid pressure |
| Noise | Noisy | Quiet | Quiet |
| Emission level | High | Lower | Low |

[a] If the pump is sized properly to reduce cycles, the wear is not different than the AAA.

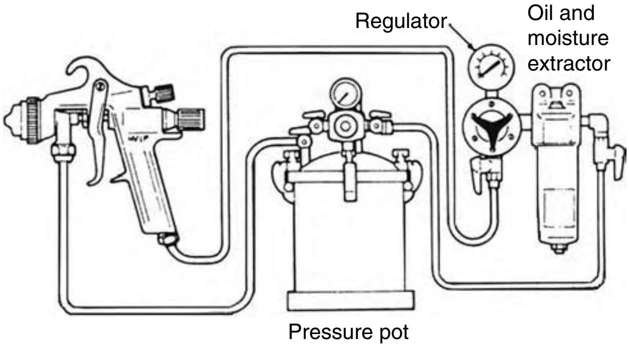


**FIGURE 6.15** High-volume, low-pressure spray system.

## 6.5 HIGH-VOLUME LOW-PRESSURE (HVLP)

HVLP gun technology is a form of air-spray that uses a restrictor to reduce the velocity of the coating material for increased transfer efficiency. It has become a favored technology by environmental agencies, because it uses about the same volume of air as a conventional air atomized gun, but it operates at much lower air cap pressures. An HVLP system is shown in Figure 6.15.

HVLP can provide higher transfer efficiency compared to other conventional spray guns without electrostatic charging. This makes it particularly useful for nonconductive surfaces such as plastic and wood.

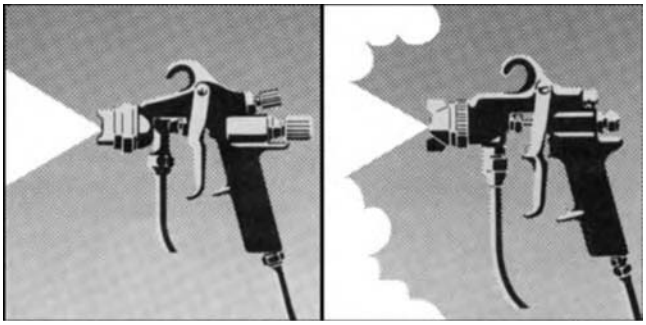


**FIGURE 6.16** HVLP versus conventional air-spray gun.

It takes a specific velocity of air to effectively overcome the cohesiveness of a paint material and atomize a coating. With air-atomized systems, more compressed air volume will increase the breakup of the material and produce finer atomization. The illustration in Figure 6.16 shows the difference in the spray pattern between an HVLP and a conventional air-spray gun.

HVLP technology delivers the same air volume at a lower pressure. This is intended to reduce the forward velocity of the sprayed material for reduced rebound and increased transfer efficiency. The lower tip velocity creates a softer fluid delivery with less overspray. Electrostatic capability can be added to an HVLP spray gun to further enhance transfer efficiency.

The amount of fluid flow and the method of applying the compressed air for atomization are what differentiate HVLP from other forms of air-atomized equipment.

Many of the early versions of HVLP equipment used electric motor driven turbines as a source for air. Unlike a compressor, a turbine works against very little backpressure so the horsepower to cubic feet per minute (CFM) ratio is reduced. Turbine systems are expensive and noisy. They can generate discharge temperatures as high as 225°F from a seven-stage turbine. This can be useful if a fast flash or accelerated cure is desired for materials such as waterborne adhesive or contact cement. However, high air temperature can also cause dry spray and other undesirable surface effects.

Turbine systems usually have a large and bulky air hose for heat resistance. The large hose makes the gun bulky to handle and inflexible. The gun handle may require insulation, making it bulky and tiresome to hold over long periods.

The turbine system can be useful for very small installations as an alternative to an air compressor or in field painting operations. Where an air compressor is present with sufficient air volume and the proper air quality (filtration and moisture elimination), it is better to work with an HVLP gun that does not require a turbine.

Most HVLP guns are run on standard compressed air. The air supply is passed through a high-volume, low-pressure, air regulator with reasonable accuracy at low pressure.

Compressed air HVLP guns use a restrictor or vortex, built into the air passage of the gun. The restrictor reduces the air output at the nozzle. A regulated inbound air pressure of 50 psi will typically produce 10 psi at the air cap. Typically, the gun is intended for operation in the range of 2–10 psi at 15–18 $\text{ft}^3$/min. If the rated input pressure is exceeded, the air volume and pressure will increase and the benefit of the HVLP is limited.

The regulator must be capable of controlling a large volume of airflow in a pressure range of 0–100 psi. Typically, the air hose for the HVLP system is larger in diameter than that of an air-spray gun. A minimum of 5/16″ diameter hose is recommended.

These guns resemble an air-atomized gun in shape and size and they can be used with the same equipment setup as the air-spray gun. They use a common 1/4″ or 5/16″ airline running to the handle directly from a compressed air line. The compressed air powered HVLP gun is more easily accepted by a hand spray operator, because it closely resembles an air-atomized gun in control, size, and appearance. An HVLP can provide good atomization for most coatings, but it may be difficult to atomize some materials with high viscosity. In some cases, air heaters are used to help control spray viscosity and improve atomization with thicker materials.

HVLP guns can be used with pressure pots or with gravity feed systems, but they do not work as well with a siphon cup.

The HVLP spray gun does produce a very soft paint pattern, and it can improve transfer efficiency when compared to an air-atomized gun. An HVLP gun may not atomize high-solids coatings well enough for class “A” surfaces, and some experienced painters complain that it is slower than a conventional air-spray gun due to lower fluid outputs. These issues are related to the restrictor. The amount of fluid output is limited by the ability to atomize. If the fluid output is too high, there is not enough velocity to break it up, and the paint droplets are coarse, so fluid volume is somewhat limited. The same issue affects the ability to atomize a material with heavy viscosity. The heavy paint material will require more energy to break it up into fine droplets. A high-solids coating applied with an HVLP may have too much orange peel.

In some situations, it is possible that the HVLP may not have sufficient output to keep up with a high-volume production operation. In other cases, the perception that an HVLP gun is too slow may be caused by the use of the wrong gun, the wrong fluid tip, or the wrong technique. Following these rules will make sure that the HVLP gun will work as designed:

- Several guns should be tested before a purchase is made to make sure that the chosen spray gun handles the coatings to be sprayed.
- Different fluid tips and air cap combinations need to be tested to find the one that works best with a particular coating material.
- Heaters can be used to help maintain a spray viscosity that will atomize with an HVLP spray gun.

Spray technique with an HVLP has subtle differences from using an air-spray gun. The gun should be held closer to the part due to the slower forward velocity of the droplets; 6–8″ is the typical gun-to-target distance. Material will build quickly with fewer and slower strokes than an air-spray gun.

Used correctly, the HVLP spray gun reduces overspray and fog in the booth, improves transfer efficiency, reduces volatile organic compound (VOC) emissions, extends the life of the filters, and reduces clean-up time.

## 6.6 ELECTROSTATIC APPLICATION

Electrostatic application is designed to enhance the attraction of the paint material to an earth-grounded surface. The basic features of the spray gun are the same, but a power supply is used to provide voltage and charge the sprayed coating material. Electrostatic attraction uses the elementary science where two surfaces that have the same charge will repel each other and unlike charges attract. Figure 6.17 shows a hand-held electrostatic spray system with an air-spray gun and Figure 6.18 is a system with an airless gun.

High-voltage electric charge is added to the atomized paint particles as they leave the gun. A voltage generator is connected to an electrode at the gun tip. The voltage source can be external or internal. When the gun is triggered, the electrode discharges a concentrated field of negative ions. Paint particles travel through this ionized area and become charged with negative ions.

The charged particles of atomized paint are directed toward the earth grounded part from the spray gun. As they approach the target surface, the electrostatic charge creates a strong attraction to the part surface. The charged particles are strongly attracted to all bare surfaces of the grounded part as shown in Figure 6.19.

Some of the particles that are carried wide of the part by compressed air are drawn to the back and edges, a phenomenon referred to as “electrostatic wrap.” Coating that wraps around edges may be beneficial on some parts, but it may have a limited benefit if no coverage is required on the back of the part.

The atomized paint droplets will be attracted to the best available ground. It is important to maintain a clean conveyor and clean hooks, and the ground should be checked regularly.

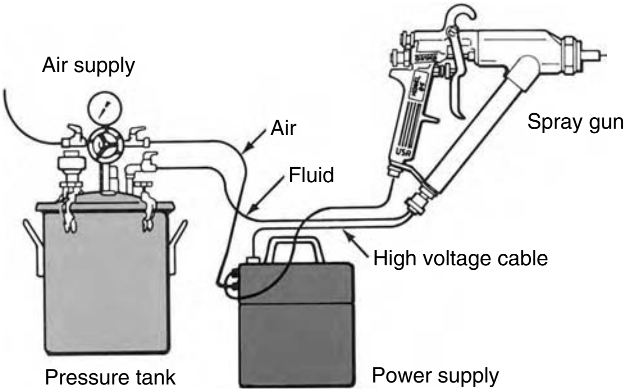


**FIGURE 6.17** Electrostatic handheld air-spray system.

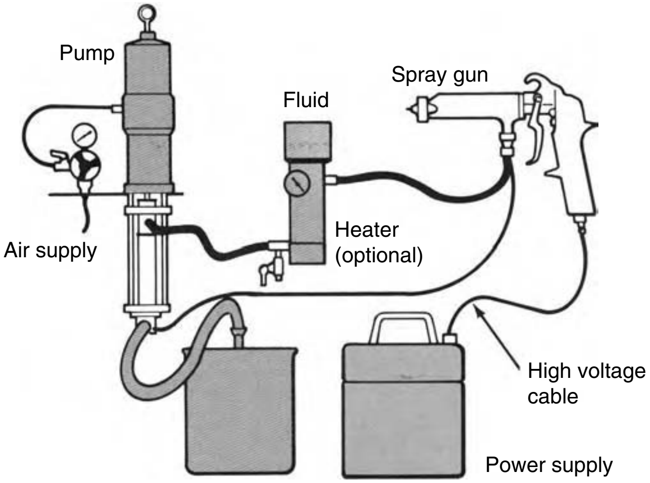

Pump
Spray gun
Fluid
Air supply
Heater
(optional)
High voltage
cable
Power supply

**FIGURE 6.18** Airless electrostatic system.

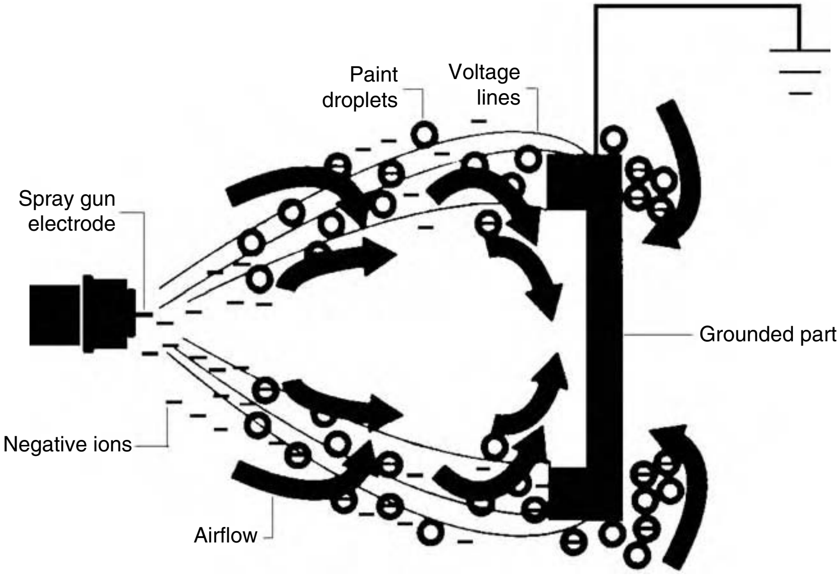

Paint
droplets
Voltage
lines
Spray gun
electrode
Grounded part
Negative ions
Airflow

**FIGURE 6.19** Electrostatic attraction.

Effective use of electrostatic systems requires certain conditions to be met.

1. The coating must be in the proper conductivity range. The majority of solvent-borne coatings will work with electrostatic systems.
2. The atomized droplets should be round and remain as wet as possible. Sometimes a slow evaporating solvent is added to maintain this wetness.

3. An electrical field must be established and maintained in the proper position to direct the charged particles toward the part.
4. Forces such as excessive spray booth velocity and abnormally dry air will interfere with the electrostatic attraction process.
5. The parts to be coated must be electrically conductive to earth ground.

Earth grounding of the part is very important to provide the maximum benefit from the electrostatic spray applicator. The National Fire Protection Association (NFPA) states that all conductive objects in an electrostatic coating area must be grounded and have a resistance of no more than 1 meg-ohm.

In a well-grounded application, the charge of the paint at the surface induces an opposite charge in the part that is equal to the field strength of the arriving ions and paint droplets. When a part is not conductive to ground, it will initially attract coating, but as more and more coating is applied, the field strength at the part surface increases rapidly and may begin to repel paint droplets. With no path to ground, the charge may build to a point where the voltage discharges and a spark occurs. Volatile solvent vapors in the immediate area can get ignited.

The process can be compared to that of a bolt of lightning that strikes the tallest object in its vicinity. As clouds move through the atmosphere, they sometimes develop a charge. The charge builds up in the cloud and then moves downward, building a channel with charge deposited along its length. Eventually, it encounters something on the ground that is a good connection. When a good connection is made, the circuit is complete and the charge is lowered from cloud to ground. The return stroke is a flow of charge (current) back to the cloud.

It is essential to have a good path to ground and maintain it religiously to avoid a discharge. Earth-ground is measured with an electrical megohm meter. A good ground has a resistance of less than 1.0 meg-ohm as recommended by NFPA. The meter uses two probes to measure resistance between the conveyor and the parts hanger and between the hanger and the part. All paint systems must have good ground to avoid static electric discharge. It is particularly important in electrostatic systems due to the high voltage of the system. The use of a megohm meter that can generate 500–1000 VDC is essential. Devices powered by small batteries are not an acceptable way of determining earth ground.

If parts are sprayed on a cart or a support other than a conveyor, they should have a cable attached to provide a path to ground. Lack of ground reduces transfer efficiency and creates an unsafe environment. All electrostatic operations should work efficiently to be sure that the parts are grounded.

### 6.6.1 MANUAL ELECTROSTATIC SPRAY EQUIPMENT

There are several types of handheld, manually triggered electrostatic spray guns used for industrial application.

- Air-spray electrostatic guns
- Airless electrostatic spray guns
- AAA electrostatic spray guns

- HVLP electrostatic spray guns
- Electrostatic rotary atomizers

Electrostatic spray guns have an electrode inside the barrel of the gun that extends to the tip. The electrode may be in the material stream or near it on the cap.

Electrostatic systems have a safety monitoring circuit that reduces the voltage output in direct relation to the approaching ground. At a closer distance to ground, the voltage drops and the current draw increases. The equipment can monitor the "closing speed" and will shut the entire system down if the rate of approach is too great. This is helpful on an automatic system where a part may be swinging free in the booth or if the high-voltage cable to the gun breaks. All resistive systems do this with no monitoring circuit. Most systems today are fully resistive and require no monitor. Bells or discs are an exception.

Automatic systems typically operate at a maximum of 90,000 V, while handheld units can operate between 20,000 and 90,000 V. Although the voltage is high, the amperage is very low. Current draw increases as the electrode nears a ground path. Safety monitoring circuitry will shut down the generator if the current draw reaches approximately 150 μA. It would take much more current draw to create a potential great enough to present a risk of injury.

The high voltage at the electrode will vary depending on the amount of current or resistance encountered between the generator and the electrode. With a resistance-free system, the voltage measured at the tip and at the generator are the same. In actual practice, the cable, the electrode, and the coating itself provide some resistance.

Not all coatings have the correct resistivity needed for electrostatic application. When a company changes from conventional air-atomized spray to electrostatic spray, they should inform their paint supplier(s) of the change so that they can confirm that the paint material is compatible with electrostatic application. If the resistance is too low, it will draw more current from the power supply, reducing the electrode voltage. If the resistance is too great, the electrostatic attraction is diminished and coating transfer efficiency and wrap will be poor.

With some equipment, the generator is located in a control panel and the signal to the gun is a high-voltage signal. Some systems use a cascade multiplier in the gun barrel. A low-voltage signal, typically 20–25 VDC, from an external power source is carried to the gun barrel where it is multiplied to the required gun tip kV. The low-voltage cable is much more lightweight and more flexible than a high-voltage cable used in external systems. Some spray guns have an alternator in the spray gun that puts out low AC voltage that is converted to the same low-voltage DC that other units send from the power supply. These systems typically have an on/off switch on the back of the spray gun, so voltage can be shut off for flushing and maintenance.

The use of electrostatic systems with waterborne coatings presents a challenge. The coating material is so conductive that it will carry current through the fluid supply lines to the coating container, creating a potential hazard and reducing transfer efficiency.

Isolation systems are used for safety reasons and for optimum system performance. Isolation stands were first used to protect workers from the "hot" container. An isolation stand is constructed of a nonconductive material that keeps

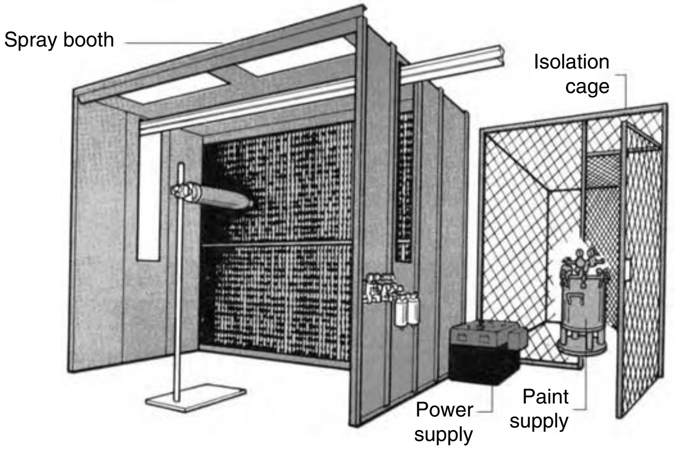


**FIGURE 6.20** Isolation cage for waterborne electrostatic spray application.

the container and the fluid supply hose away from ground and typically, they are enclosed in a cage where operators cannot access the container without automatically grounding the system. An isolation cage used with a waterborne coating is shown in Figure 6.20.

An alternative to isolation of the fluid supply is a voltage-block system. One type of voltage-block system features two single-stage, pneumatically operated reservoir-type pumps, one as a transfer pump and the other as a spray pump. Shuttle valves with quick-connect couplings connect the pumps during operation. The electrostatic generator supplies voltage to the spray pump and the pump transmits a charge to the coating material. During operations, the shuttle valves alternately connect the transfer pump to either the grounded paint-supply source or to the electrostatically charged spray pump.

Another type of voltage block system has a pneumatically actuated rotary valve that works in conjunction with a material supply chamber to fill the valve and rotate it to an isolated area in the valve to supply coating to the electrostatic applicator. An isolation material is used to constantly wash the rotary valve and create isolation between the coating supply containers.

In both cases, the shuttle valves provide an air gap to maintain electrical isolation between the charged coating material and any grounded material or equipment. These arrangements provide a continuous flow of charged material while keeping the charge isolated from the fluid supply.

Another alternative to an isolation system is an externally charging electrostatic gun or bell. This type of applicator has charging probes located on the exterior of the applicator. The external probes allow the application of waterborne paints electrostatically without isolating the paint supply.

In many cases, the voltage is adjusted to its maximum output level. However, many coatings, particularly, light metallic coatings, operate better at lower voltage. Coverage problems, such as edge build-up, can usually be resolved by adjustments to triggering points, shaping air, gun-to-target distance, and so forth.

**TABLE 6.5**
**Solvent Polarity**

| Non or Low Polarity | Medium Polarity | High Polarity |
|---|---|---|
| Mineral spirits | Ethyl acetate | MEK, MIK, acetone |
| VM and P naphtha | Butyl carbitol | Isopropyl alcohol |
| SC-100, SC-150 | Ethyl alcohol | |
| Xylol, toluol | Methyl alcohol | |
| Butyl acetate | Methyl acetate | |

### 6.6.2 COATING FORMULATION FOR ELECTROSTATIC APPLICATION

In handheld systems, the polarity of the solvent should provide a coating that is stable under voltage at above 10 meg-ohm $\mathrm{cm}^3$ (typical). For efficient application, it is usually recommended not go beyond 200 meg-ohm $\mathrm{cm}^3$ (see Table 6.5).

Addition of polar solvents may be necessary when the coating is so dead, or so nonconductive that without the solvent it will not accept a charge.

Electrostatic systems require special care and maintenance practices. All parts of the system must be kept clean, including the outside surfaces of the fluid hose and spray gun. Any possibility of a direct path to ground, resulting in a system shut down, must be eliminated. The exterior of the gun must be kept clean of overspray that will allow the voltage to "track back" to the operator who provides a great ground path. Automatic systems are even more demanding with regard to system cleanliness, because they operate at even higher voltages.

Advantages and disadvantages of electrostatic spray.

### 6.6.3 ADVANTAGES

- Material savings due to electrostatic attraction and wrap; more material on the parts, less on the filters
- Reduced VOC emissions
- Reduced booth cleaning and frequent filter changes
- Increases in production rates
- Reduced equipment wear because of lower fluid and atomizing air pressures

### 6.6.4 DISADVANTAGES

- Minor coating adjustment may be necessary.
- The part must be conductive to ground or must be prepped with a solution that will provide a ground path.
- Conveyors and parts carriers must be well grounded and kept clean.
- The relatively high cost of an electrostatic gun compared to that of a conventional air atomized gun or and HVLP gun. Efficiency should still provide the necessary return on investment (ROI).

An electrostatic spray system can be a great advantage in increased transfer efficiency, reduced VOC emission, reduction of labor, and reduced coating usage. On the other hand, if it is not fully understood, not properly used, or not maintained, it can become an expensive air-spray gun.

There are a few simple rules to remember in order to use an electrostatic system effectively and safely.

- The parts being coated must be electrically conductive to ground.
- Part carriers, racks, fixtures, carts, and so forth must be designed to provide a consistent ground path, and must be kept clean in order to maintain a good ground path.
- All items in the vicinity of the spray booth must be grounded. They can develop a static charge and discharge it to ground. A spark may ignite volatile vapors.
- The spray operator should never wear gloves that isolate them from the grounded gun handle. If gloves are worn, they should be designed with a conductive palm or a hole should be cut that allows skin to contact the gun handle. In addition, metallic objects, coins, watches, keys, and so forth that are normally kept in pockets should be removed as they, also, can build up a static charge. Rubber boots or insulated shoes should not be worn; leather soles will dissipate any static charge.
- Flooring in and near the spray booth should be conductive. In older buildings where wooden floors are still found, sheet metal should be used as a covering, making sure all pieces are mechanically connected to one another and the booth walls.
- It is very important that only items designed for electrostatic spray be used. Air hoses should contain a ground wire built into the jacket. Air or fluid moving through the hose can create a static charge. Be sure to use the proper high or low-voltage cable for your gun. Do not mix brand “A” with brand “B”.
- The voltage should be turned off before servicing or cleaning the electrostatic device. If the gun has a built in cascade type generator or multiplier, the atomizing air must also be turned off. Be sure the gun is wiped clean and that no solvent remains in the fluid line before turning on the voltage.

### 6.6.5 AUTOMATIC SPRAY EQUIPMENT

Automatic spray equipment can add substantial capability to a system by increasing the amount of coating that can be delivered in a given time and controlling the volume of output. Automatic application reduces the labor required for application and it contributes to the consistency and quality of the product. Many factors enter into the design of a paint application system and contribute to the decision to apply paint with manual equipment only or add automation to the process.

The benefit of using automatic equipment is the ability to use any number of applicators in one spray zone and the consistency and repeatability of an established automatic application program. An individual sprayer can apply a limited amount of material to a surface in a given amount of time. An automatic spray station is limited only by how many applicators are in use for that spray station. The chief reasons why a company will invest in automation are to produce more volume, achieve more consistency, and save money through reduced material usage and reduced labor cost.

Operation and maintenance of an automatic system requires a higher skill level than a manual spray operator. Instead of a quick adjustment of the fluid and air pressure from a pressure tank or the fan spray pattern at the back of the gun, the operator will be responsible for several important controls. Depending on the level of automation and electronically controlled functions, the operator will need to at least monitor and maintain

- Applicator operation
- Fluid flow controls and components
- Equipment programming
- Applicator movers
- Material supply system
- Safety interlocks

Once they have been properly set, automatic gun settings should not be continually adjusted, but they should be routinely monitored. In spite of the added responsibility and skills required for their operation, automatic application equipment can provide needed volume and superior control. An automatic application system can cover substantially more area than a single manual operator.

In order to take advantage of the additional capacity, the application equipment must be installed with complimenting control equipment and it must be well maintained, workers must be well trained, and good scheduling practices must be in place to ensure that the system capacity is used. Racking arrangements must be more precise and consistent to get the best transfer efficiency. Part recognition systems must be well designed and maintained to make sure that the guns are triggered accurately.

There are many different models and types of automatic application equipment from many different manufacturers, but they break down into three main categories; air-spray guns, bells, and disks.

### 6.6.5.1 Automatic Air-Spray Guns

An automatic air-spray gun closely resembles a manual spray gun without a handle and manual trigger. It may be mounted in a stationary position or designed for use with a reciprocator or robot. They have one or dual spray heads and different spray angles to best fit the application. Automatic spray guns are triggered by a part identification system that "reads" the position and size of the part as it approaches and turns the guns on and off at the appropriate times. A more detailed triggering system uses a manually entered part number or style code at a manual input station (MIS) that utilizes a detailed application program that is specific to that part style and color.

Fluid tips and pattern shapes can be changed for different applications, making these guns flexible for a variety of products and paint materials. Air-spray guns will typically provide better penetration into recesses than a bell or disk. Typical transfer efficiency can be very good, if parts are properly racked and the triggering programs are well defined. However, the air pressure required for atomization can result in more overspray than a bell. The bell atomizes the paint in a finer droplet and more narrow range, so the grounded part is able to attract a higher percentage of the paint sprayed. The bell also has a lower forward velocity, so the paint is less likely to be carried past the target by the force of the spray.

#### 6.6.5.2 Rotary Atomizers

A system that uses a “bell” (rotary atomizer) or a disk is sometimes referred to as a true electrostatic system. The rotating bell or disk provides the atomization, and the high voltage causes the coating to go to the part. The rotation of the bell or disk causes the paint to move parallel to the target with the voltage off and the high-voltage field redirects the atomized droplets toward the target. Shaping air is also used with bells to control paint pattern size and aid penetration into recessed areas. Shaping air is used to direct the droplets toward the part where electrostatic attraction helps to draw the paint droplets onto the target. Figure 6.21 shows atomized paint at the edge of a bell.

Bells range in size from about 15–70 mm in diameter. Rotational speeds are anywhere from 10,000 to 60,000 rpm. Usually, a smaller bell diameter will have a faster rotational speed. The bell can be fed from a pressure pot as shown in Figure 6.22 or from a larger container.

Typically, a faster rotational speed will provide more finely atomized paint. High solids and waterborne coatings may be difficult to atomize at rotational speeds below 15,000 rpm.

The charged paint droplets will take the shortest path directly to the part. Although this provides high transfer efficiency, it can cause some difficulty in coverage

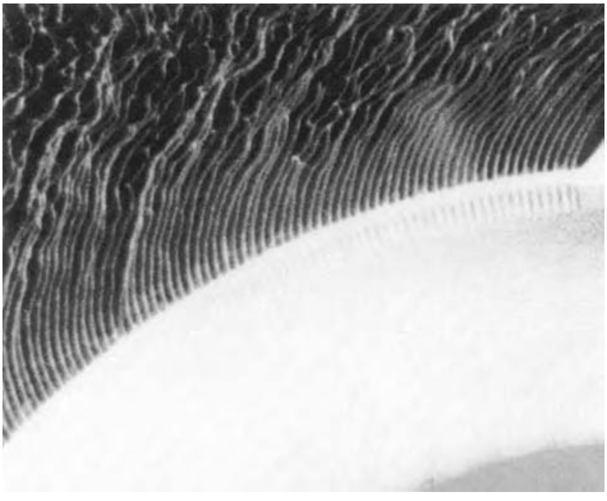


**FIGURE 6.21** Paint filaments from the serrated edge of a rotating bell.

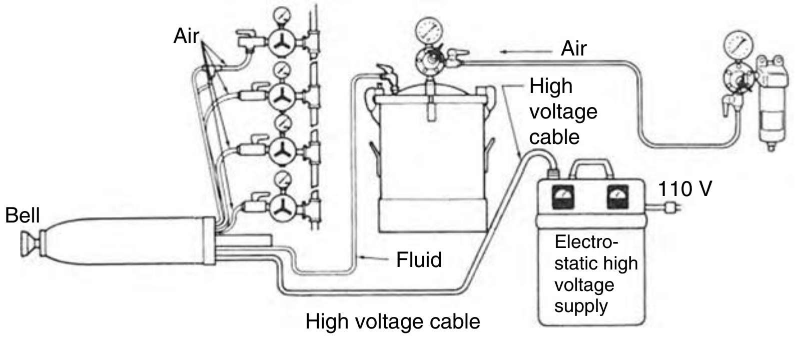


**FIGURE 6.22** Electrostatic bell system.

inside recesses. When the paint takes the shortest, most direct route to ground, it will be more likely to build on the flatter surfaces and the edges. Any crevices, interior corners, or complex shapes will be difficult to coat due to electrical resistance.

With a bell, the charged droplets in the air do not travel to the part with much velocity. Without the force of compressed air to drive them into the crevices and corners, manual touch up may be the only way to achieve the necessary coverage.

If the product is flat sheet steel, the transfer efficiency will be extremely high and the film buildup will be very even without touch up. Voltage or triggering adjustments can be made to overcome excess buildup on the edges.

Most bells use air as the bearing surface for the shaft that turns the bell. Air is pressurized between 60 and 100 psi and delivered between the high precision bearings and the shaft, creating a thin but very stiff cushion of air. The shaft can rotate on the air cushion, free of metal-to-metal contact.

On a bell, the fluid is normally fed through a tube down the center of the turbine shaft where it flows evenly over a cone at the back of the cup. The centrifugal force of the rotating bell evenly disperses the fluid to the edge of the rotating cup. The fluid passes through small holes on the outside of the bell, it is centrifugally atomized and attracted to the grounded work surface by electrostatic attraction. The shaping air is directed from an opening behind the bell to provide pattern control from 15″ to 48″ in diameter. The inside of the bell is shown in Figure 6.23.

A bell is often used on applications where the best appearance on the part is required. A bell atomizer virtually eliminates “mottling” and produces less “orange peel” than other automatic applicators. The bell can be mounted on a single or multiaxis gun mover or it can be used on a robotic arm to obtain more than three axis of motion.

Disks are much larger in diameter and they spray perpendicular to the target. Increasing or decreasing the rpm of the rotary atomizer controls the droplet size of atomized paint. The disk sizes can range from 6″ to 12″ in diameter. Like the bell, the larger diameter disk usually has a slower rotational speed.

As mentioned previously, an automatic spray gun employs compressed air to deliver the paint to the part. It will provide somewhat better penetration of the Faraday areas and deep recesses but has the potential to generate more overspray. It is important

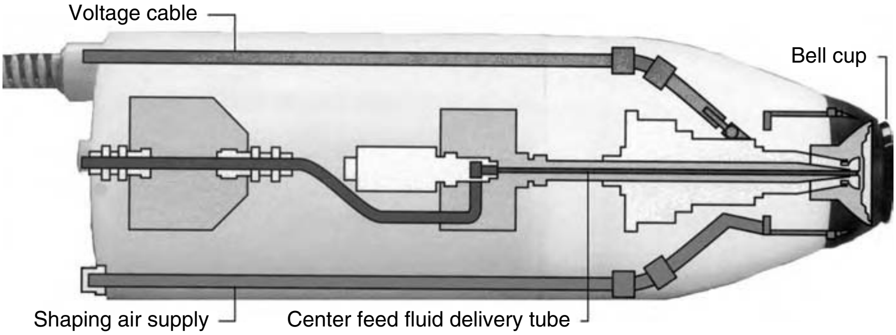


**FIGURE 6.23** Inside of a rotary bell.

to consider this and compare the efficiency of a bell or disk and the related touch-up required to that of an automatic electrostatic spray gun when planning a system. Testing is important to see just what device works best.

Typically, a bell works well for simpler geometries requiring high transfer efficiency and even film or for the first application in a multiple application process. An air-spray gun may be the best application device for more complex geometries or for cut-in and touch-up.

The combination of automatic electrostatic and hand spray will always be more cost effective than a hand-spray-only operation. The return on investment for the automatic equipment will vary with the application. Jobs that have very low production rates may not be candidates for automation. However, process consistency improvements can provide greater first time quality and often justify the cost.

### 6.6.5.3 Automatic Spray Supporting Equipment

Automation requires much more than just the correct selection of application equipment. There are many small but important application equipment and fluid flow control components. Multiple gun stations must be designed for accurate and controllable flow of air, fluid, voltage, and movement. Hoses must be kept as small and as short as possible for quick color change and low material waste. Color change manifolds should be located near the spray station so that the purge of material from the supply line is quick and there is very little material in the line. Color change programs should be written to fully utilize the material from the color change manifolds to the applicators to further reduce waste and color change time.

### 6.6.5.4 Gun Movers

Automatic guns are sometimes mounted in a stationary position. More often, they are mounted on a reciprocator or robot. There are long-stroke (Figure 6.24) and short-stroke reciprocators with vertical or horizontal movement. There are multiaxis gun movers that can move the guns in three dimensions: in/out, up/down, and in the direction of the conveyor. Moreover, there are robots (Figure 6.25) that can

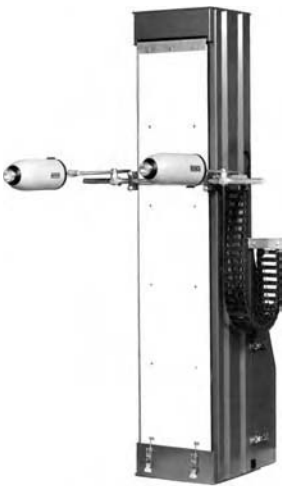


**FIGURE 6.24** Long stroke reciprocator with bells.

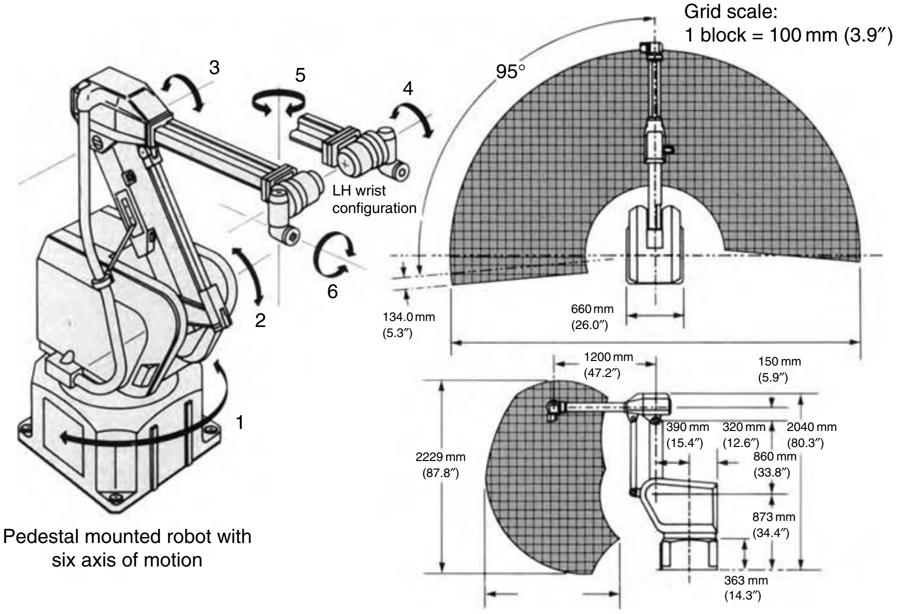

Grid scale:
1 block = 100 mm (3.9″)
3
5
4
95°
LH wrist configuration
6
2
1
134.0 mm (5.3″)
660 mm (26.0″)
1200 mm (47.2″)
150 mm (5.9″)
390 mm (15.4″)
320 mm (12.6″)
2040 mm (80.3″)
860 mm (33.8″)
2229 mm (87.8″)
873 mm (34.4″)
363 mm (14.3″)
Pedestal mounted robot with six axis of motion

**FIGURE 6.25** Movement of robotic arm.

move the gun in multiaxis patterns similar to a manual operator but with much more precision.

The use of a gun mover is product dependent. They can help the guns to cover more surface of product and get into deep recesses, such as cars, office furniture, or appliance shells.

One important thing to consider is that the machine selected is a durable piece of industrial equipment. Examine the construction and motion design to make sure that it is solid and will last. These machines will be expensive, so the testing must be thorough.

The stroke of the machine must be electronically integrated with the product and the line speed and controlled accordingly to avoid irregular patterns on the part surface. Establishing the correct stroke distance and stoke speed based on the line speed, surface to be covered, and desired film thickness will provide uniform coating application.

Reciprocator mounting bars can be configured with a variety of patterns for different products. They can be mounted over the top of product on a floor-mounted conveyor or in vertical positions to coat from the side. One short stroke reciprocator can hold a double bar of three or four spray guns or bells each. This kind of versatility is one of the advantages of automation. Several guns can be brought to bear on the parts in a very short time span. The number and position of the guns can be designed to provide excellent coverage with low overspray.

#### 6.6.5.5 Robotic Painting

A spray gun or bell mounted on a robotic arm provides the advantages of manual application (focused application and multiaxis movement) with much more accuracy and consistency. This provides an opportunity for improved quality, productivity, and reduced labor.

Robotic arms come in many different sizes with different control options. A typical software driven controller can manage color change, provide analog fluid and air control, part queuing, arm homing, conveyor synchronization, path and function editing and simple lead through, and Cartesian teaching methods.

With a slim wrist design, the robotic arm can provide 360° of roll and 90° of pitch and yaw with flexible spatial coverage. Large, complex parts can be painted very effectively with exceptional precision using a robotic arm.

#### 6.6.5.6 Summary

There is a wide variety of automatic spray equipment for liquid paint application. It is very important to conduct testing of the equipment to determine the best system for a given application.

When the application devices are tested, it is also important to evaluate the fluid flow control devises. A fluid flow control system or device may work very well with one type of material and work poorly with a different material. The equipment must be compatible with the flow rate and viscosity of the material being sprayed. For example, a very low flow rate with a lower solids material, such as two-component urethane on plastics, will need a small, sensitive regulator to provide the necessary control. If the material type and flow rate are changed, it may be necessary to change regulators. Remember that all of the fluid handling devices (regulators, static mixers, and flow meters) are not infinitely adjustable or interchangeable. They will work well within a certain range of flow, so you need the correct size for the flow rate that will be needed for a certain production line.

Always make sure that employees are well trained in the operation and maintenance of the spray equipment. Follow safety guidelines and keep up to date on new innovations in equipment and control options.

## 6.7 ALTERNATIVE APPLICATION METHODS

In addition to spray application, there are several alternative ways to apply liquid paint to industrial products.

### 6.7.1 DIP COATING

In a dip coating application, the part is simply immersed in a tank of paint. Excess paint drains back into the tank once the part is removed. Parts may be handled in batches or with a conveyor.

Dip tanks can be built in any size needed for small or large parts. Provisions must be made for circulation, filtering, and control of temperatures and viscosity. Because of the fire hazard involved, dip operations using flammable paints must be equipped with $CO_2$ fire extinguishing systems and dump tanks.

#### 6.7.1.1 Advantages of Dip Coating

- Simple equipment
- Low-skilled labor requirement
- Easily automated
- Close racking of parts
- Various part shapes can be mixed
- Little paint is wasted if the part is allowed to drip over the tank

#### 6.7.1.2 Limitations of Dip Coating

- Viscosity control is critical. If the paint is too viscous, too much paint is used (wasteful) and film thickness is too high. Low viscosity results in paint films that are too thin. Consequently, corrosion resistance may be too low for primers and hiding power may be inadequate for topcoats.
- Possible settling of the paint in the circulation system.
- Gradual tank contamination is possible. Parts entering the tank must be clean and dry to avoid carrying in contaminants.
- Some parts are hard to immerse, because trapped air keeps them afloat.
- Tanks must be large enough to immerse the entire part.
- There is a fire and toxicity hazard associated with large volumes of paint solvents.
- Film thickness control is a problem. Paint may become trapped in recesses and drain slowly or not at all. On vertical surfaces, the paint tends to be thicker at the bottom of a panel than at the top. This is caused by an increase in viscosity as the paint loses solvent while draining. It often results in fatty edges that can later break off under thermal or mechanical shock.

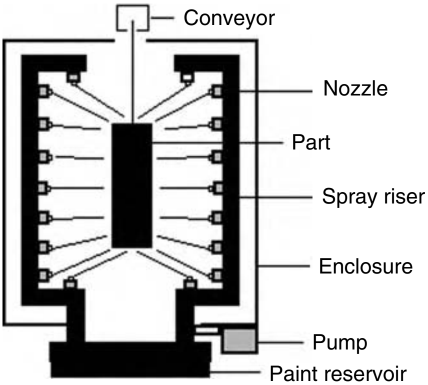


**FIGURE 6.26** Flow coating.

- The drain-off area must be cleaned regularly. Since this is usually done manually, some dried paint may fall into the circulation system and clog the filters, pumps, and nozzles.

## 6.7.2 FLOW COATING

In a flow coating operation, the part is held over a tank and a stream of paint is pumped over the part through a nozzle (see Figure 6.26). The excess paint drains into the tank and is recirculated over the parts. The variables that are important for flow coating include pumping, filtering, viscosity, temperature, ventilation, and fire control.

### 6.7.2.1 Advantages of Flow Coating

- Simple equipment
- Little labor required
- Easily automated
- Dead air spaces can be coated if a stream of paint can be directed upward into the recess
- Smaller volumes of paint are required, because the parts need not be immersed
- Little paint is wasted if the parts are allowed to drain over the tank

### 6.7.2.2 Limitations of Flow Coating

- High solvent loss by evaporation. Solvent must be replenished on a regular basis.
- Possible settling of the paint in the circulation systems.
- Fire and toxicity hazards associated with the high solvent loss.
- Inability to coat certain recesses and inside surfaces.
- Gradual paint contamination if the paint rinses dirt, salts, oils, and so forth from the parts.

- Film thickness control is a problem. Paint may become trapped in recesses and drain slowly or not at all. On vertical surfaces, wedging may occur resulting in fatty edges.
- The drain-off area must be cleaned regularly. Since this is usually done manually, some dried paint may fall into the circulation system and clog the filters, pumps, and nozzles.

Dip and flow coating methods should be considered when high production painting of relatively simple shapes is required and quality appearance and corrosion resistance is not important. Viscosity and film thickness control are the major problems to be expected. Efficient use of paint and low labor rates are the primary advantages.

These processes are limited to waterborne coatings because of environmental considerations. High-solids coatings do not lend themselves to these types of application because of the higher viscosities that cause poorer flow characteristics and high film builds. Paints with high solvent content produce too much VOC for most installations and they create an unsafe working environment.

### 6.7.3 ROLLER COATING

A roller coating operation is capable of coating large areas in the form of sheet or strip at high speed and with a continuous and even thickness of paint or varnish. The rollers can also be used to laminate plastic film to metal substrates.

There are two methods of liquid transfer for roll-coating systems on flat sheets. One system uses three rollers and the second uses four rollers. In the first process, the liquid is fed between the feed and applicator rollers rotating in opposite directions. The stream of paint is then fed through the rollers onto the sheet. The third roller acts as a pressure roller to ensure that the sheet comes into correct and even contact with the wet applicator rolls (see Figure 6.27).

In the four-roller process, a fountain roller picks up liquid from a trough, transfers it to the feed roller, which in turn presses it to the applicator roller. The fourth roller acts as the pressure roller, as in the three-roll system. In coil coating applications, where both sides of the sheet are coated, the four-roller system is used. The applicator rollers act as pressure rollers.

Fountain and feed rollers are normally made of stainless steel, while the applicator roller has a steel core covered with a rubber, gelatine composition, or

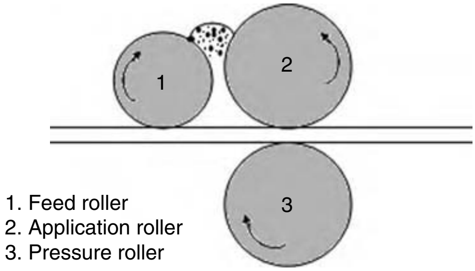


**FIGURE 6.27** Roll coating.

polyurethane face. These surfaces become deformed during use and need to be remachined to offer a continuous smooth surface. Gelatine rollers are resistant to many organic coatings but are not resistant to water-based coatings. Polyurethane rollers produce a solvent and abrasion resistant surface. They are normally found as applicator rollers on fast running coil coat lines.

#### 6.7.3.1 Advantages of Roller Coating

- Smooth, even, dust and “fat edge” free films can be produced
- Films dry relatively quickly
- No excessive solvent or paint losses due to evaporation occur
- There is no fire hazard

#### 6.7.3.2 Disadvantages of Roller Coating

- Limited to thin sheet stock
- Not able to apply the variety of finishes used in spray coating

### 6.7.4 CURTAIN COATING

Curtain coating is a sophisticated method of pouring a continuous film of lacquer or paint over flat sheets. The sheets are conveyed under a trough with an adjustable slot. The trough acts as a pouring head and control of the gap regulates the volume of material, controlling the film thickness deposited on the sheets. Curtain coating works well for coating flat sheets of metal or wood.

A second conveyor moves the coated panel away from the gap. Initial application efficiency is excellent and any material that does not adhere to the product is recirculated to the trough by means of a pump.

In some instances, moisture-containing substrates are prewarmed in a tunnel prior to coating. The warm panel aids the set-up characteristics of the paint or lacquer. An alternative is to heat the lacquer with a heat exchanger located between the reservoir and trough.

The most important part of curtain coater is the adjustment slot (or gap) in the trough. The gap can be accurately controlled to develop predetermined film weights. The trough and slot must be kept scrupulously clean, because any dirt or solid material will break the curtain and cause a surface defect.

# 7 Transfer Efficiency and Spray Technique

Transfer efficiency is the measurement of the percentage of the paint material sprayed that provides coating on the parts versus the percentage that is lost in the spray process. The type of spray gun is very important, but it is only part of the picture. The extent of automation and electronic control equipment, the cleanliness and maintenance of the system, the skill and training of the operator, the coating material, the product being sprayed, the flow rates, and spray booth air velocities will affect the transfer efficiency of any spray equipment. Table 7.1 provides a comparison of different technologies in field and lab tests, and shows the relative transfer efficiencies of each.

## 7.1 SPRAY GUN CONTROLS

There are several related adjustment points on a gun that allow the operator to control the size and shape of the pattern, the amount of atomization, and the amount of fluid coming out of the gun.

For manual guns, there are typically two adjustments located at the rear of the gun handle. One knob will adjust the amount of air going to the air nozzle, providing control of the size and shape of the pattern. The other knob adjusts the fluid needle travel, allowing more or less fluid flow. The fluid volume should not be adjusted with the knob on the gun unless the gun is being used with a siphon system. Adjustment

**TABLE 7.1**
**Transfer Efficiency of Liquid Paint Spray Equipment**

| Spray Process | Transfer Efficiency(%) |
|---|---|
| Conventional air spray | 15–40 |
| Conventional airless | 20–50 |
| Conventional air-assisted airless | 30–60 |
| Conventional HVLP | 30–60 |
| Electrostatic airless | 40–70 |
| Electrostatic air spray | 40–80 |
| Electrostatic air-assisted airless | 50–85 |
| Electrostatic HVLP | 60–90 |
| Electrostatic bell atomization | 70–95 |
| Electrostatic disk atomization | 80–95 |
| Electrical atomization | 95–98 |

by fluid needle travel is unstable and causes premature wear to the needle and seat. If a spray gun is used with a pressure system, then the fluid flow should be controlled with the fluid regulator, and the knob should be left in the full open position.

Adjustment starts by following the manufacturer's recommendations for needle and nozzle selection from their charts. The charts will indicate the proper range of fluid and air pressures.

The fluid pressure is set from the chart and the atomization pressure is added until the pattern is uniform and consistent. A good starting point for the atomization pressure could be as low as 5 psi. The pattern can then be tested to see if the paint is properly atomized and additional pressure can be added if it is needed. Excess atomization air will generate more velocity and reduce transfer efficiency.

If the atomization is not fine enough, the air pressure should be increased about two or three pounds at a time and tested each time it is increased. Once the correct amount of atomization is reached the pattern size and shape can be adjusted with the pattern adjustment knob on the spray gun.

The normal position for the ears on the air cap is parallel to the floor to produce a vertical fan pattern. This assumes spray gun movement from left to right. To create a horizontal fan spray pattern, the operator can turn the ears or turn their wrist 90°.

Usually, when the fluid pressure is increased it is necessary to increase the atomizing air pressure. The two air pressure controls are adjusted to provide the correct volume of material with uniform atomization and a minimum of velocity. The best overall delivery pressure is always the lowest pressure that will adequately provide the correct volume of paint and the correct atomization.

If the atomizing air is too high relative to the amount of fluid being delivered, it may produce excess velocity and dry spray. If it is too low, the fluid droplet size may be too large (inadequate atomization) and the surface may have orange peel.

If too much fluid is applied, the film may be too heavy with more risk of sags. If the amount of fluid applied is too low, it may cause lightly coated areas on the part and dry spray.

## 7.2 APPLICATION TECHNIQUE

It is possible to do several things wrong and still produce a good finished product. However, proper technique will improve the quality of the finish, reduce overspray, reduce labor, and increase the life of the spray equipment.

Proper technique begins with an examination of the spray gun. A brief inspection of the system may find some detail that needs to be adjusted before the gun is triggered. Some of the things to look at include

1. Is the trigger easy to pull back, and does it return smoothly and quickly when released?
2. Are the air and fluid nozzles properly installed?
3. Are the fluid and air hoses the correct size?
4. Is the fluid hose free of pinch points?
5. Are the hose connections tight?

### 7.2.1 ATOMIZATION

After the system inspection has confirmed that the gun is ready for spraying, a test pattern should be sprayed on cardboard. A full oval shape with an even distribution of paint is needed to produce a quality finish. Spray enough paint on the cardboard to allow it to run. The runs should be equal all across the pattern. If the runs are heavier on one side of the pattern, the air cap may be defective. Rotate the air cap 180° and respray the cardboard to see if the heavy runs shift sides. If they do, replace the air cap.

The amount of paint delivered to the gun tip is determined by the amount of product to be painted and the time available to spray it. The amount of atomizing pressure is determined by how much energy it takes to break up the paint stream into a uniform pattern. The best spray pressure is the lowest possible level at which the job can be done.

### 7.2.2 GUN POSITION

A spray gun needs to be held at a constant angle to the part to help apply uniform film buildup. If the spray gun is tilted, the distance between the nozzle and the part surface is not consistent, and film deposition will not be uniform. More paint at a greater velocity will contact the part in the one area of the pattern. This causes poor hiding and dry spray at one end of the pattern and heavy film at the other. This tilted position is sometimes referred to as heeling or toeing the gun (see Figure 7.1).

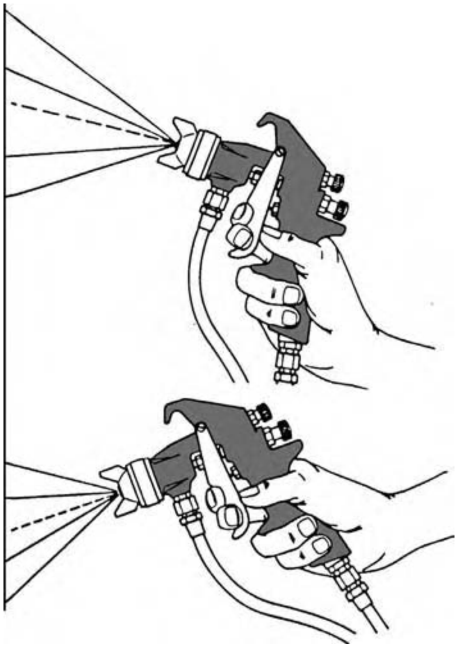


**FIGURE 7.1** Improper stroke, tilting.

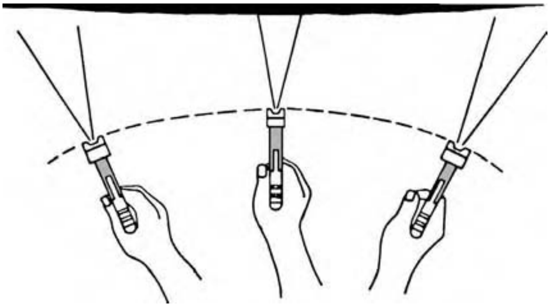


**FIGURE 7.2** Improper stroke, fanning.

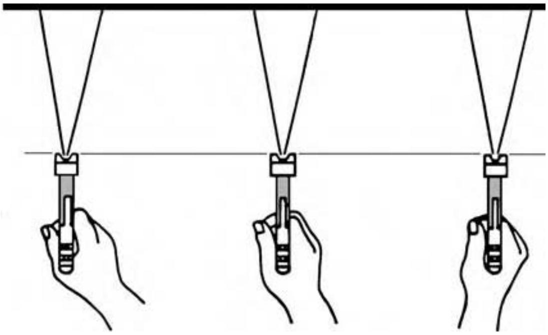


**FIGURE 7.3** Proper spray stroke.

Heeling/toeing is an easy way to recognize technical error and one that is easily corrected. Figure 7.1 shows the incorrect position. Proper application requires a level stroke.

Another common error is arcing or fanning the spray gun from side to side (see Figure 7.2). This will occur when the operator hinges the spray gun from the elbow instead of the shoulder and wrist. The pattern is not kept at the same distance from the product during the entire spray stroke, and the film deposits heavy in the center and light at the edges.

Proper spray application requires the use of the wrist, elbow, and shoulder working together during the stroke. The average spray stroke is 36″. The arm moves side to side in a horizontal motion. The wrist must be flexed as the arm strokes from side to side, attempting to maintain a consistent gun-to-target distance (see Figure 7.3). The proper spray stroke will produce the most uniform film with the least risk of runs, sags, or dry spray.

### 7.2.3 GUN DISTANCE

Gun distance and gun speed are also very important factors in spray accuracy and uniform paint application. The distance from the nozzle tip to the product affects the wetting of the paint and the appearance of the coating.

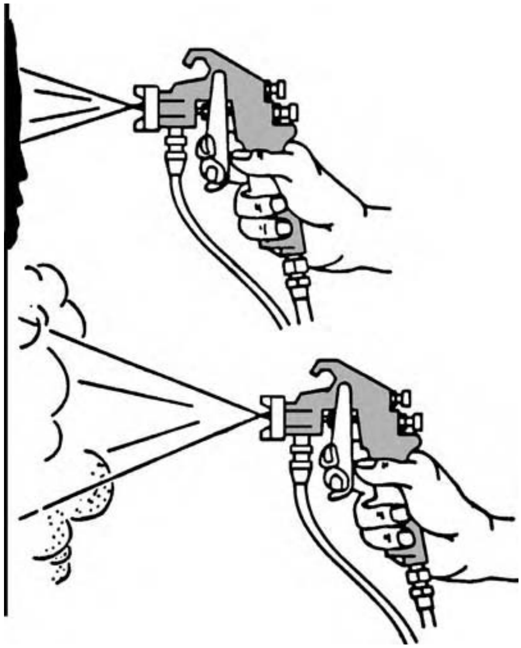


**FIGURE 7.4** Improper gun-to-target distance.

Solvents evaporate as the coating leaves the gun. The correct gun-to-target distance works in harmony with the specific solvent blend in the coating and provides the proper “wetness” when the coating hits the target. If the gun is too far from the product, there is more risk of dry spray. If the gun is too close to the target, the film may sag (see Figure 7.4).

If the distance between the spray gun and the target increases or decreases, the wetness of the paint film will be affected by the evaporation rate of the solvents in the paint blend. The typical distance from the target for hand spray is 6″–12″. Each coating may have a slightly different distance that seems to work best, and the spray gun and gun adjustment will also affect the wetness of the film. It is important to be as consistent as possible while stroking the gun.

### 7.2.4 GUN SPEED

Another important factor in accurate film deposition is speed of the stroke. The stroke speed of the spray gun should be kept consistent for the best material utilization and to conserve the energy of the operator.

The “gyroscopic painter” technique should be avoided. Excessive pivoting of the spray gun uses more paint material than necessary, makes a mess of the booth walls and ceiling, and wastes energy.

The correct speed allows for an even wet film of material to be applied in one stroke. If the stroke is too slow, it may cause sags and runs, solvent pop may occur, and it is more difficult to keep up with production. If the stroke is too fast, it may cause dry spray, uneven film buildup, and exhaustion of the operator.

Gun speed should be maintained at a comfortable and even pace. The fluid pressure and the air nozzle pressure are set to work in harmony with the speed of the stroke.

### 7.2.5 LAPPING

The gun stroke should be overlapped in a precise pattern to ensure complete and uniform coverage. The amount of the spray pattern that is overlapped should be 50% of the total pattern width. If the gun delivers a 12″ pattern for each spray stroke and each stroke overlaps by 6″, it is called a 50% overlap. The center of the spray pattern is aimed at the wet edge of the previous stroke (see Figure 7.5).

Sometimes a spray pattern is "crosshatched" to build additional film thickness and to provide uniform thickness and coverage. Crosshatching refers to a pattern that is stroked vertically and then horizontally.

The spray gun should be triggered before the pattern reaches the part and released after the pattern leaves the part to avoid a heavy area. Triggering on the part will leave a large deposit of material in one area, because the coating will not be fully atomized for a split second after the trigger is pulled.

The size of the spray pattern should be related to the part being coated. Large panels can be efficiently coated with a full pattern. For slender work, the pattern should be small enough to avoid excessive overspray.

In order to apply an even film, the spray pattern must be uniform. It is useful to spray a sample pattern on a piece of cardboard to make sure that there is no problem with the fluid nozzle or air cap. Some examples of faulty spray patterns are shown in Table 7.2.

When coating a large panel, the conventional method is to cover the surface with horizontal strokes. The stroke starts about 6″ off the part, and the trigger is pulled

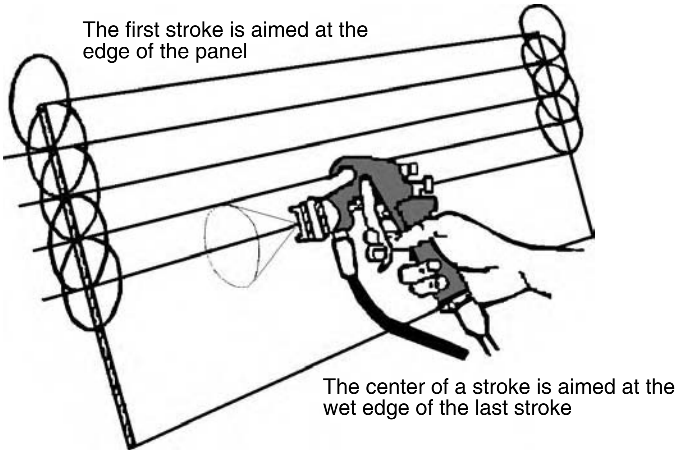
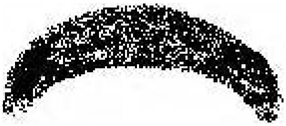
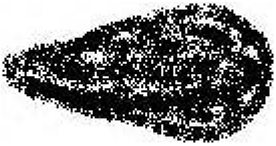
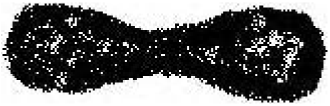
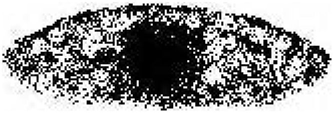

The first stroke is aimed at the edge of the panel
The center of a stroke is aimed at the wet edge of the last stroke

**FIGURE 7.5** Proper overlap stroke.

## TABLE 7.2
## Spray Pattern Problems

| Pattern | Cause | Correction |
|---|---|---|
|  | 1. One of the side ports of the air nozzle is clogged | 1. Use paint thinner to remove dried paint; do not probe into the holes with anything harder than brass |
|  | 1. Fluid build up on one side of the fluid nozzle<br>2. Damaged fluid nozzle | 1. Remove air nozzle and wipe off fluid nozzle<br>2. Replace damaged fluid nozzle |
|  | 1. Air pressure is too high<br>2. Spray pattern is too wide<br>3. Fluid pressure is too low | 1. Reduce air pressure<br>2. Reduce fan width<br>3. Increase fluid supply |
|  | 1. Air pressure too low<br>2. Excessive fluid velocity or too much fluid | 1. Increase air pressure<br>2. Use smaller fluid nozzle orifice, reduce fluid pressure |
| Spitting | 1. Loose fluid nozzle<br>2. Fluid needle not seating (dirt)<br>3. Loose or missing packing nut or dried fluid packing<br>4. Fluid connection is loose | 1. Tighten fluid nozzle<br>2. Clean fluid nozzle seat area<br>3. Tighten packing nut or replace missing or dried fluid packing<br>4. Tighten all fluid supply connections leading to the spray gun |

just before the gun tip reaches the edge of the part. The trigger is released just after the gun tip moves off of the other end, and a new stroke begins in the other direction with the gun moved down to produce a 50% overlap.

The strokes can be vertical if the operator is comfortable with the motion and able to produce consistent and uniform film build.

Coating the edge of the panel with parallel strokes can reduce the amount of overspray. The gun does not have to be moved off the edge of the part. An illustration in Figure 7.6 shows this technique.

A box shaped part should be coated on the corners first, and then the flat surfaces are covered with the same technique as a panel (see Figure 7.6).

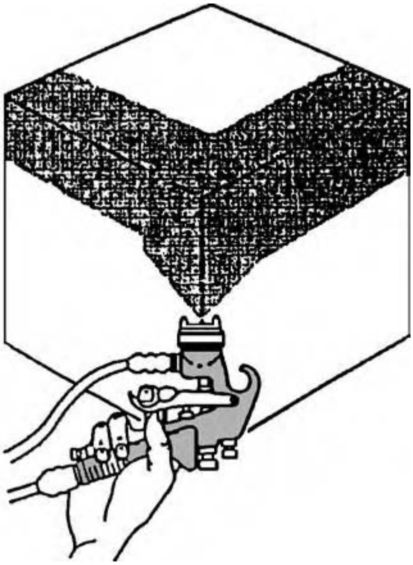


**FIGURE 7.6** Paint application on a corner.

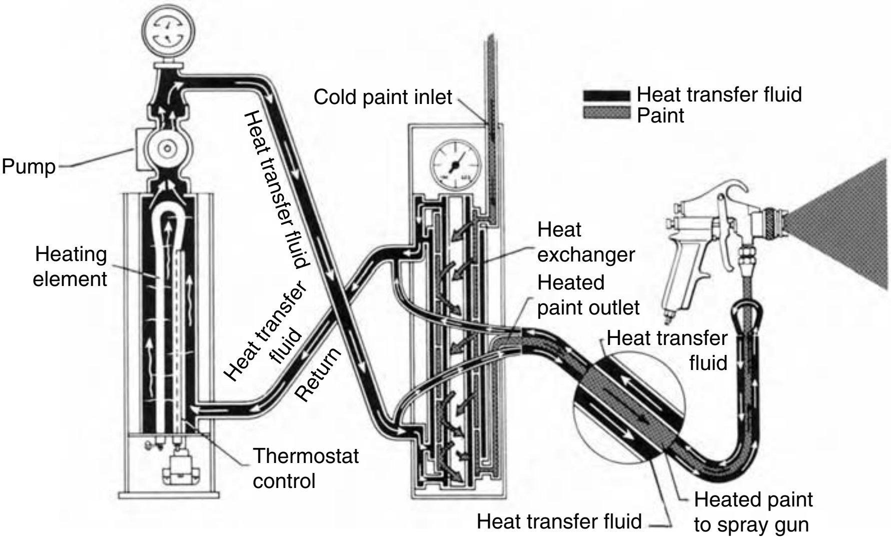

Cold paint inlet
Heat transfer fluid
Paint
Pump
Heat transfer fluid
Heating element
Heat exchanger
Heated paint outlet
Heat transfer fluid
Heat transfer fluid
Return
Thermostat control
Heat transfer fluid
Heated paint to spray gun

**FIGURE 7.7** Paint heating system.

### 7.2.6 HEATED SPRAY

The addition of an in line paint heater can provide several advantages, particularly considering the high-solids content of a compliant liquid coating. The heater will not only help to achieve a correct spray viscosity, but will also provide consistency so that the paint is less sensitive to temperature, and the operator can apply a more uniform film without adding additional solvents.

The spraying of heated paint enables the low boiling solvents to evaporate between the spray gun and the surface, leaving the high boilers to level the material. The increased viscosity of the paint will allow more material to be deposited without sagging.

Paint heaters can be fitted for different types of application systems; they can be attached to a booth, or they can be portable for field applications.

There are several types of paint heaters that can provide consistent paint temperatures at a specific flow rate. A typical heater circulates heated water or oil through a heat exchanger. The paint is heated as it passes through the heat exchanger on its way to the spray device (see Figure 7.7).

Electric paint heaters are often used in medium to small paint supply and circulation systems. Paint heaters are typically capable of raising the paint temperature to 70°F from the temperature on the inbound side of the heater.

# 8 Spray Booths

A liquid spray booth is an enclosure around the spray operation that provides containment of the oversprayed paint and controls the spray environment. The spray booth includes an exhaust fan to create negative air pressure inside the booth. The exhaust air contains the overspray, directs paint solids to the filters, and directs the solvent vapors to atmosphere or an abatement system. The booth provides a clean and safe environment for the operator and smooth airflow to enhance paint transfer efficiency.

For liquid spray systems, the airflow can be either vertical in a down draft design or horizontal in a cross draft design (see Figure 8.1). Airflow is necessary to contain the paint overspray by creating a slight negative pressure inside the spray booth.

## 8.1 NFPA REQUIREMENTS

The agency that produces the standards that govern spray booth design and operation is the National Fire Protection Association (NFPA). NFPA 33 provides the safety guidelines for spray booth construction and sets the standards for airflow and electrical requirements.

NFPA 33 requires that spray booths be substantially constructed of noncombustible materials and prohibits the presence of an open flame or spark-producing equipment in a spray area. The dimensions of the "spray area" are defined differently, if the ventilation system is interlocked to the spray equipment in a way that prevents operation of the spray equipment without ventilation. If the booth exhaust is

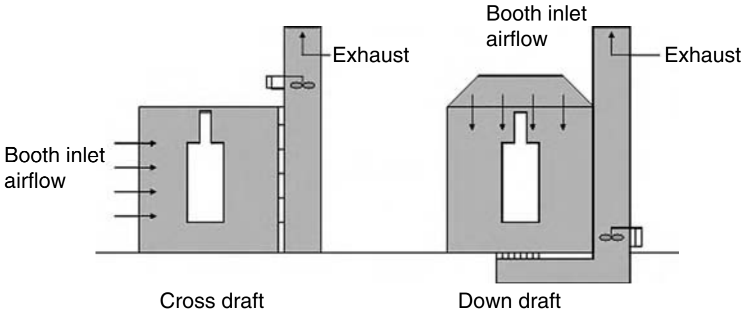


**FIGURE 8.1** Dry filter spray booths.

interlocked with the spray equipment, then electrical wiring or equipment within 5 ft (1.5 m) of the booth openings must be explosion proof or intrinsically safe. If the exhaust is not interlocked, the hazardous area extends to 10 ft (3 m).

Spray booths are designed with sufficient air turnover to maintain a solvent concentration that is below 25% of the lower flammable level (LFL) of the material being sprayed. The LFL is the lowest flammable concentration of a gas in air in which a flame can be propagated when given a source of ignition. This is also called 100% LFL and can be used interchangeably with %LEL (lower explosive limit) (see Table 8.1). Different solvents have different LFL values.

**TABLE 8.1**
**Lower Explosive Limit of Some Commonly Used Solvents**

| Solvent | $ft^3$/gal of Vapor of Liquid at 70°F | LEL in % by Volume of Air at 70°F |
|---|---|---|
| Acetone | 44.0 | 2.6 |
| Amyl acetate (iso) | 21.6 | (1) 1.0 |
| Amyl alcohol (n) | 29.6 | 1.2 |
| Amyl alcohol (iso) | 29.6 | 1.2 |
| Benzene | 36.8 | (1) 1.4 |
| Butyl acetate (n) | 24.8 | 1.7 |
| Butyl alcohol (n) | 35.2 | 1.4 |
| Butyl cellosolve | 24.8 | 1.1 |
| Cellosolve | 33.6 | 1.8 |
| Cellosolve acetate | 23.2 | 1.7 |
| Cyclohexanone | 31.2 | (1) 1.1 |
| 1,1 Dichloroethylene | 42.4 | 5.9 |
| 1,2 Dichloroethylene | 42.4 | 9.7 |
| Ethyl acetate | 32.8 | 2.5 |
| Ethyl alcohol | 55.2 | 4.3 |
| Ethyl lactate | 28.0 | (1) 1.5 |
| Methyl acetate | 40.0 | 3.1 |
| Methyl alcohol | 80.8 | 7.3 |
| Methyl cellosolve | 40.8 | 2.5 |
| Methyl ethyl ketone | 36.0 | 1.8 |
| Methyl n-propyl ketone | 30.4 | 1.5 |
| Naphtha (VM&P) (76° naphtha) | 22.4 | 0.9 |
| Naphtha (100° flash) safety solvent—Stoddard solvent | 23.2 | 1.0 |
| Propyl acetate (n) | 27.2 | 2.8 |
| Propyl acetate (iso) | 28.0 | 1.1 |
| Propyl alcohol (n) | 44.8 | 2.1 |
| Propyl alcohol (iso) | 44.0 | 2.0 |
| Toluene | 30.4 | 1.4 |
| Turpentine | 20.8 | 0.8 |
| Xylene (o) | 26.4 | 1.0 |

NFPA also states that spray booth exhaust must have an adequate supply of make-up air to maintain proper operation of the exhaust system. Without air supply, there is a risk that the booth will lose its negative pressure and solvent vapors or paint solids can escape the booth.

## 8.2 AIR MAKE-UP

Air make-up (AMU) systems are designed to supply air into the building or directly to the spray booth. A fan draws outside air into the AMU housing and directs it through a discharge outlet into the building or directly into an air inlet plenum that is connected to the booth. The volume of air should be adjustable for booth balancing purposes. Dampers or variable frequency drives can be used for adjustment. The air can be cooled or heated as needed. Humidity controls are also sometimes added to the supply air. The AMU heater is often located on the roof of the building, but it may be mounted on the ground or suspended above the spray booth. The AMU should be located far enough from the spray booth exhaust stack and in a position where the vapors from the booth exhaust cannot be entrained in the AMU intake air stream.

## 8.3 BOOTH EXHAUST STACKS

The exhaust stack height is affected by local environmental regulations, building height, and the surrounding area. The exhaust stack should extend above the roofline for 30–50% of the building height to make sure that the exhaust is carried up into the prevailing winds. A 20-ft building should have a stack height of 6′–10′ above the roof.

Stacks should be longer in areas with high buildings, tall trees, or other nearby vertical obstructions. High neighboring obstructions can create low-pressure areas and interfere with the exhaust stream so that vapors and fine paint solids may not be carried up into the prevailing winds.

## 8.4 SPRAY BOOTH SIZING

The interior work area of the booth can influence the transfer efficiency of the sprayed coating and the ability of the spray booth to contain overspray. Spray booth sizing depends on the size of the products to be sprayed, the equipment used to apply the paint, and time required to achieve full coverage. Booths come in a variety of stock sizes from 4′0″ *W* × 7′0″ *H* × 6′0″ *D* (work chamber) to 20′0″ *W* × 10′0″ *H* × 9′0″ *D*. Many spray booths are custom fabricated to fit the products that will be coated and paint system.

It is very important to make sure that a spray booth has enough area to efficiently apply the coating and maintain containment of the overspray. There are some very practical guidelines to booth sizing that can help with selection.

In some spray operations, the part is moved into the booth without an overhead conveying system. A small batch operation may use carts to bring parts into the booth.

A large truck frame or a piece of heavy equipment may be moved into a booth on track in the floor. These batch systems require a booth that is large enough to allow freedom of movement around the part and clear access to all surfaces with enough room for the equipment, the part, and the operator.

Conveyorized systems will have an overhead or floor mounted conveyor that affects the booth sizing. Adequate vertical height, width, and depth are required to make sure the booth functions properly.

### 8.4.1 SPRAY BOOTH HEIGHT

The product being painted should be no lower than 30″ off the floor so that the operator does not have to bend too much and the bottom of the part is accessible. From the top of the part to the hook site should be at least 30″ in an electrostatic operation to avoid painting the hook, and 36″ is preferred. In a nonelectrostatic operation, the conveyor should be at least 30″ above the spray zone to avoid painting it.

### 8.4.2 SPRAY BOOTH WIDTH

The width of the booth is related to the number of spray stations in the booth and the size of the part to be coated. Each automatic spray station should be at least 4′0″ away from the booth walls or another station. Therefore, the minimum booth width (working chamber) for one automatic spray station is 8′0″. The minimum for two spray stations is 12′0″ wide. This applies to conveyorized systems running at some production line speed. Very small batch operations, or conveyors at very slow speeds, can use a 6′0″ wide booth for manual application.

### 8.4.3 SPRAY BOOTH DEPTH

The depth of the work chamber is related to the thickness of the product. The product needs to be kept at least 3′ away from the exhaust filter bank in a cross draft booth, and there must be adequate space for spray stations or manual operators to move freely.

### 8.4.4 INTERIOR WORKING DIMENSIONS

The sizes indicated above are minimums. In most cases, it is helpful to provide more work space so that no paint is lost from the booth interior and the filters are not too close to the spray guns.

Containment of paint overspray can be assisted by the addition of entrance and exit vestibules that profile the opening into the booth.

In manual operations, the part size and line speed make a larger width necessary to give the operator time to spray. In the case of two manual sprayers in the same booth, 5–6 ft should be left between the sprayers and 5–6 ft from the booth wall. Also, manual spray operators tend to start spraying as soon as the part enters the booth, so an entrance and exit vestibule of at least 3′0″ is recommended to help keep overspray inside the booth.

## 8.5 SPRAY BOOTH EXHAUST SIZING

The spray booth exhaust, measured in cubic feet per minute (CFM), is determined by multiplying the width of the working chamber times the height, times the recommended air face velocity. Typical face velocity in a spray booth is 100–120 feet per minute (FPM) for manual spray operations and 50–80 FPM for automatic spray operations.

Fans are often sized bigger to allow for paint load in the filters during production. As filters load with paint, the face velocity drops and the booth may not be able to properly dilute the air and prevent solvent accumulation or contain overspray.

A booth that is 10′0″ wide × 10′0″ high used for manual painting would require 12,000 CFM with clean filters (10′ × 10′ × 120 FPM = 12,000 CFM). If the booth has product openings, the square footage of opening should be multiplied by 100 FPM and added to the total CFM. For example, with a 2′ × 5′ product opening in each side of the booth, the additional air needed for the booth is 2000 CFM.

$$2' \times 5' \text{ product opening} \times 2 \text{ (one on each side)} \times 100 \text{ FPM} = 2000 \text{ CFM}$$

The air volume for the booth openings is added to the volume needed to supply the required face velocity to get the total exhaust volume.

$$12{,}000 + 2{,}000 = 14{,}000 \text{ CFM total}$$

## 8.6 FILTRATION

Exhaust filtration is designed to capture paint solids and allow solvent vapors to pass through into the exhaust air stream. The exact filter arrangement is related to the process requirements, the material being sprayed, application equipment transfer efficiency, and amount of overspray.

Bulk media is less expensive and easier to deal with than filter pads or bag filters. Many systems use two layers of filters to provide the needed particulate arresting efficiency while keeping the overall cost down and simplifying filter change. The first layer of filters is less expensive. It is designed to collect the bulk of overspray and is less efficient on the small particle sizes. The second filter layer is much more efficient on the small particle sizes and initially more expensive. This arrangement allows the operator to replace the lower cost media more frequently while extending the life of the high efficiency second-stage filter. A typical arrangement would be a 90% + efficient bulk media over 99% + efficient bag type filter. The filtration efficiency must effectively remove nearly all of the particulate from the air stream to protect downstream equipment and the environment.

In a dry filter booth, NFPA requires that a manometer or magnahelic filter gauge be installed on the exhaust filters to measure pressure drop. A typical setting for this filter gauge might be 0.25″ of water, as measured in inches of water column (WC), although this will vary dependent on how the fan was sized, booth velocity, and filter resistance.

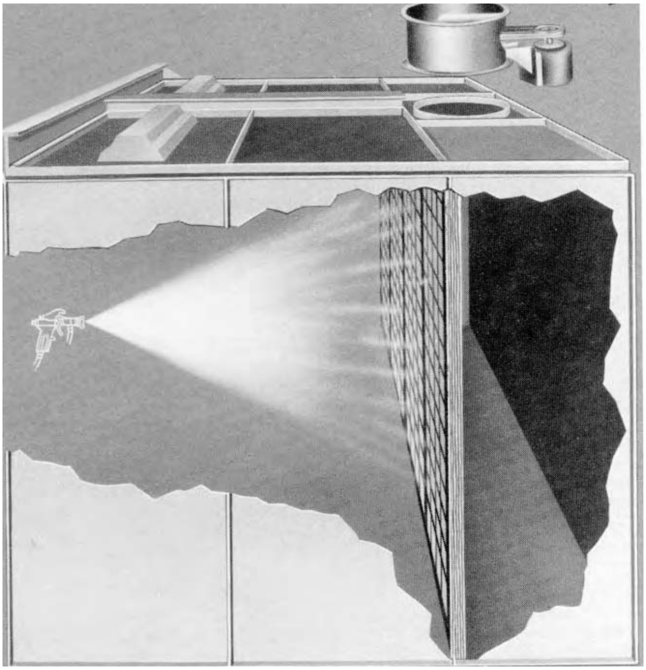


FIGURE 8.2 Dry filter spray booth.

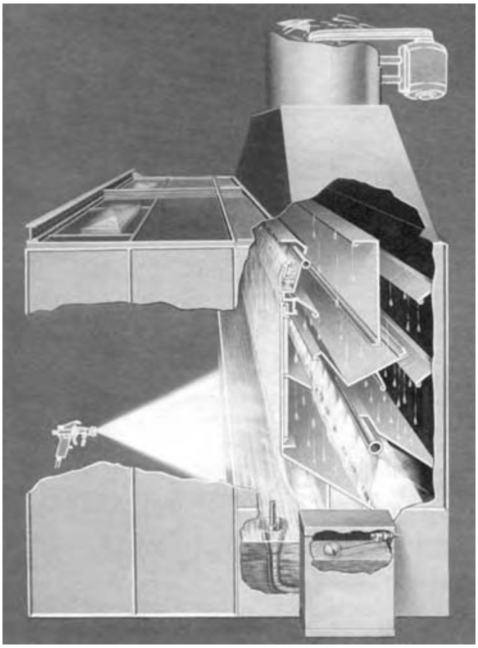


FIGURE 8.3 Water wash spray booth.

As the filters become loaded, the pressure will drop and the gauge will move up. When the filters reach a load level that restricts airflow, they are overloaded and need to be replaced. The point at which this happens should be noted on the filter gauge and the filters should always be changed before they reach that level. If the filters seem to need changing too frequently, the coating material may have changed, the spray gun transfer efficiency could be going down, there could be a problem with the exhaust fan, or other filter materials should be evaluated.

The exhaust portion of the spray booth may use dry filters, or it may use a water curtain to capture paint solids. As the filter media gets loaded with oversprayed paint solids, the air volume will decline, and the filters will need to be changed to maintain optimum airflow and transfer efficiency and to prevent loss of containment of the oversprayed paint solids and vapors. Dry filter booths are much less expensive than water wash booths, they require less maintenance, and they are also recognized as best available technology. Used filters are typically less difficult to dispose of than liquid paint sludge (Figure 8.2).

A water wash booth has a curtain of water that flows at the back of the booth or in the floor of the booth, a pump, and some type of sludge separator with chemicals to neutralize the coating material. Maintenance is typically higher than a dry filter booth, and the wet sludge is a hazardous waste. The primary advantage of a water wash booth is that the airflow remains constant, because the overspray is collected in the sludge where it cannot restrict the exhaust. This also means that production is not interrupted for a filter change in the middle of the day that requires large gaps or down time in the line to minimize the risk of part contamination (Figure 8.3).

# 9 Curing

Curing is the process of converting the applied wet paint to a dry film. The paint may cure by solvent loss (lacquers and emulsions), chemical reaction (enamels), oxidation (oil base house paints), melting and resolidifying, or melting and cross-linking (powder coatings). Energy is usually required for dependable and consistent drying of industrial coatings.

Air-dry paints rely on solvent evaporation into the surrounding atmosphere. The temperature and humidity will have a profound impact on the drying time. Low temperature and/or high humidity will not provide sufficient atmospheric heat to rapidly dry the paint. Ovens or dehumidification equipment can be used to speed up the drying time and make it more predictable.

Paint cure ovens are enclosures in which the coating on the painted parts is forced to cure more rapidly than by air-drying alone. Usually, they are insulated and provided with a means of exchanging solvent-rich air for fresh air. They range from small batch type boxes to large conveyor equipped structures that can be hundreds of feet long.

Finishing systems often use convection ovens, infra red (IR) ovens, and ovens that combine convection and IR equipment for drying and curing. Various oven suppliers have their own design methods that can be effective. However, a few standard concepts should always be considered, regardless of the manufacturer.

## 9.1 CONVECTION CURING

A convection oven cures by circulating heated air around the part to heat the substrate. The part conducts heat into the paint and the paint dries from the heat. The convection oven uses a heating system that recirculates hot air through supply duct and distributes it throughout the oven. The basic components include the insulated walls and roof, the supply duct, and the burner box, which houses the fan(s) and heat source (Figure 9.1).

The curing of organic coatings is a function of time and temperature as defined by the paint supplier. Typical oven cure cycles range from 10 to 30 min. The time and temperature required depend on the type of coating and the substrate. The cycle must be long enough to bring the substrate to the desired temperature, and maintain it for the prescribed time.

### 9.1.1 DUCT DESIGN

Cure oven ductwork should be designed to circulate air in a way that will maintain even heat throughout the oven without excess turbulence. The best location for the duct is the oven ceiling. Ductwork is located in the corners and between conveyor passes to provide uniform distribution of air. Adjustment cones can be used for air balance.

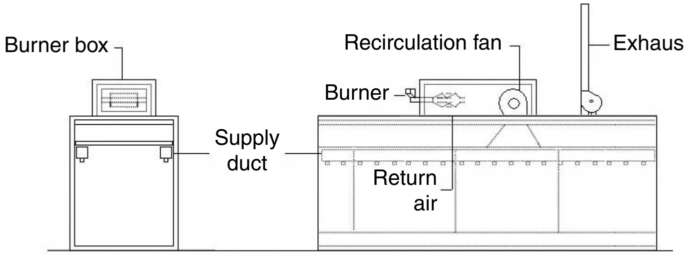


**FIGURE 9.1** Convection cure oven.

The floor is also an acceptable location, arranged under the conveyor with air passing up through the parts (Figure 9.1). Floor duct will interfere with movement and cleaning inside the oven.

Recirculation fans and ducts are designed to ensure adequate air movement within the oven. This prevents solvent vapor build-up in dead spots and provides for the constant movement of hot air over the part surface. Without this air movement, paint heat-up would be slow and vent loss rates would vary, slowing the process, and possibly causing film defects. Typical duct exit velocities are on the order of 1000–2000 ft/min (305–610 m/min).

### 9.1.2 OVEN FUELS

Gas is most commonly used in process ovens, because it is readily available, it is easy to control, and it is less expensive than other fuels. High-quality gas burners feature up to a 40:1 turn down ratio, providing efficient operation at various load levels. The gas burner is typically mounted in the side of the burner box upstream from a centrifugal recirculating fan, which discharges through a transition duct and into the distribution duct. The burner box can be mounted on top of the oven, on the side of the oven, on the end of the oven, or underneath the oven.

An oven can function quite well with an electric heater, and the design is very similar to the gas burner box. Sheathed electric heating elements take the place of the gas burner in a package-type heater with a built-in centrifugal recirculating fan. Electric ovens require more time to reach the operating temperature and to cool to ambient conditions. In addition, electricity is still more than twice as expensive as natural gas. Using a gas price of \$1.00 per 100 $ft^3$ of gas the cost per 1M Btu is \$10.00. Using an electric cost of \$0.08 per kilowatt-hour, the cost per 1 M Btu is \$23.43.

Steam can also be used to provide heat to a convection oven. Like gas and electric heating systems, a steam heating system uses a recirculating convection-type burner box. The return air should be filtered with high-efficiency air filters to prevent the steam heat exchanger from clogging. For a steam heat exchanger, a self-operating regulator with indicator should be used with a strainer to protect the valve. In addition, a bypass line with throttling valve and self-acting steam control valve should be installed for proper heat control. Steam is typically not practical for curing higher temperature products unless a facility already has a boiler with excess capacity.

### 9.1.3 MATERIALS OF CONSTRUCTION

The oven interior skin is typically 20-gauge aluminized steel, because it has superior heat resistance compared to galvanized or cold-rolled steel. The outside oven skin is typically 20-gauge galvanized, aluminized, or painted cold-rolled steel. The oven trim material should match the oven skin. Mild steel interiors are not recommended, because the surface can rust and cause contamination inside the oven.

The insulation is typically 4-lb density mineral wool or equivalent fiberglass, and the thickness should be 4″ for processes up to 300°F and 6″ for processes from 300°F to 500°F. For temperatures greater than 500°F, 6-lb density mineral wool is recommended. The roof and walls should have the same panel thickness, but the floor may be plain concrete, aluminized skin, or insulated oven panels. Elevated ovens should have an insulated floor. Floor-mounted ovens are acceptable with an aluminized skin; however, there will be significant heat loss through the floor. For exterior ovens exposed to the weather, 6-lb density insulation is typically provided in increased thickness.

## 9.2 INFRA RED CURING

IR curing can be a great asset for faster oven process times, and it can also contribute to the quality of the finish. To use IR properly, it is important to understand of what it is and how it works.

IR energy is a form of electromagnetic radiation. There are three wavelengths of IR energy, measured on the electromagnetic spectrum in microns, between visible light and microwaves. These wavelength bands are shortwave (0.76–2.3 μm), medium wave (2.3–3.3 μm), and long wave (3.3–1,000 μm) (Figure 9.2).

IR energy is transmitted from an emitter and directed at a target. Depending on the wavelength of IR and the nature of the coating, the energy can behave in one of

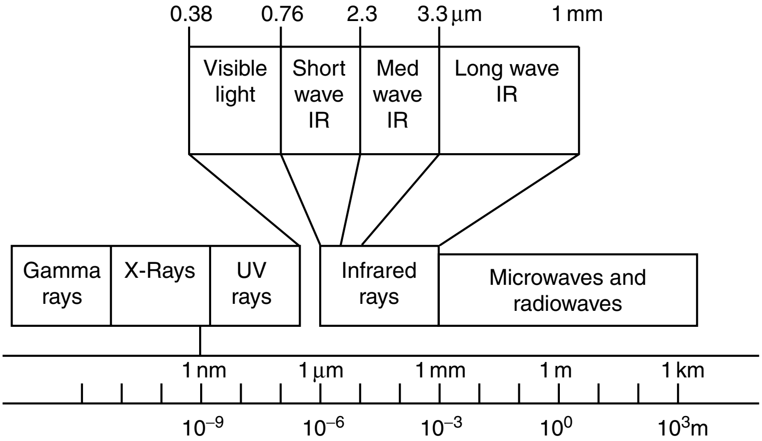


**FIGURE 9.2** Electromagnetic spectrum.

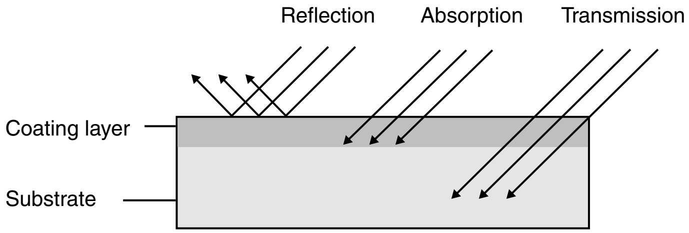


**FIGURE 9.3** Infra red behavior.

three ways: reflection from the surface, absorption into the coating, or transmission into the substrate (Figure 9.3).

Energy reflected from the surface has little or no benefit, although it is possible that it will be reflected back to the part surface by the reflectors located around the emitters. Transmission into the substrate will contribute to the cure of the coating, but it may not be a very efficient use of the IR energy with substrates that have relatively fast thermal conductivity. The advantage of IR is fully realized when the energy is absorbed by the coating, creating molecular oscillation, and generating heat.

Most organic coatings will absorb the highest percentage of energy in the medium wavelength. Short-wavelength absorption characteristics are quite low; most of the energy is transmitted into the substrate, leading to a smaller processing window and more color sensitivity. Long-wavelength IR provides less surface heating because of low electromagnetic energy levels. It is best suited for wood drying or similar low-temperature applications.

In order to fine-tune the appropriate IR system for a specific coating, testing is required. Shortwave IR may be suitable for some preheat situations, but care must be taken to avoid overexposure. Shortwave systems are very useful for products that have relatively simple geometry where the surface can be uniformly exposed to the emitters.

Medium-wave IR provides good absorption characteristics with less intensity than shortwave, and it is more flexible for a variety of coatings and different parts. Long-wave IR is useful where low wattage per square inch is required.

The nature of energy transfer by light makes it difficult to maintain uniformity over irregular surfaces. In order to react to various parts of different mass and shape, the intensity or position of the emitters must be adjusted by the operator or a programmable logic controller (PLC). This lack of flexibility limits the number of applications where it is practical to use IR alone for curing, particularly if the throughput will vary in size, shape, and mass. In situations where the mass-to-surface ratio and the part geometry are changing rapidly, it may be difficult to control the amount of energy and avoid excess or insufficient cure.

A combination of IR and convection can make an excellent oven, providing flexibility, saving space, and offering dependability and reasonable energy efficiency. For example, an oven may be equipped with an IR section at the entrance to begin the cure process prior to entry into a larger convection zone. It can shorten the overall cure cycle and reduce the risk of contamination that may occur in the convection zone.

It can also be zoned to effectively react to different masses on the part and accelerate cure on heavy substrates.

In some cases, IR can be the best, if not the only, way to cure a coating. Very massive parts that would require impractical cure times with convection heating can be cured fairly quickly in an IR oven that is properly designed. Testing is required to determine the precise intensity of the emitters and the optimum arrangement.

## 9.3 OVEN MAINTENANCE AND CLEANING

Oven maintenance is a critical issue in the design. It will be necessary to clean the inside of the oven, so the duct interior and exterior must be accessible, and the surfaces should be smooth so that they can be washed or vacuumed. Man doors and swing-in dock lights should be included where possible. For high-quality finishing systems, such as clear-coat or plastic lines, interior lighting may be used to facilitate cleaning the oven.

## 9.4 OVEN EXHAUST

Cure ovens must be exhausted to remove solvents, gases, and the by-products of the combustion. Oven exhaust also creates a negative environment in the oven enclosure, which helps to contain the oven atmosphere at the product openings.

The amount of air exhausted from the oven is based on the amount of solvent that is carried into the oven and the by-products of combustion. The exhaust volume must be high enough to prevent a loss of gases from the openings. Excess exhaust will unnecessarily increase the cost of oven operation.

Exhaust is required to prevent the buildup of solvent vapors to explosive levels. Safety codes require that solvent vapor levels should not exceed 25% of the lower explosive limit (LEL). 10,000 $ft^3$ (280 $m^3$) of fresh air must be supplied for each gallon (3.79 L) of solvent evaporated.

## 9.5 OVEN FILTRATION

The negative air pressure in the oven may attract particulate from the facility that can cause dirt defects on parts. Vacuuming the oven interior regularly will help to prevent contamination from building up in the oven and becoming a problem.

Another way to help avoid an oven dirt problem is by providing return air filtration. A filter framework is built into the return air opening of the burner box and high-temperature filters are installed in the frames. While the efficiency of the filters varies for each application, a typical combination would feature a row of 30%-efficient filters serving as the prefilter layer for a secondary layer of 90%-efficient filters. This prevents the blower from circulating dirt onto the parts and constantly sweeps the oven (Figure 9.4). High-efficiency filters may not require a prefiltered air stream.

If return air duct is used, the filtration should not be located in duct that is in close proximity to the parts. Return air filtration should only be located in the return opening.

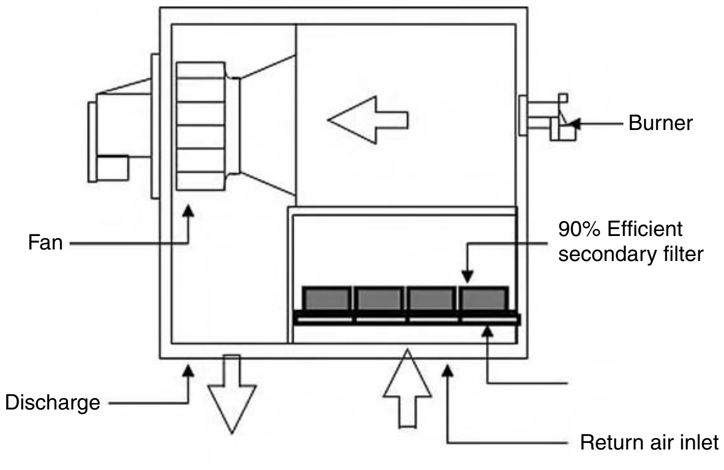


FIGURE 9.4 Return air filtration.

## 9.6 OVEN LOCATION

Ovens can be located directly on the floor, elevated on support steel, or located on the building roof. A floor-mounted oven with product openings in the sidewall should feature some method of heat containment as described previously, and the floor should be insulated to reduce heat loss. Elevated ovens remove process heat from the floor and save floor space. An elevated oven can cost considerably more than a floor-mounted oven because of increased installation costs and additional materials. Bottom entry and exit openings in an elevated oven will provide the best possible heat containment.

## 9.7 THE IMPACT OF CATALYSTS ON CURING

Catalysts are chemicals that are added to the paint to accelerate cure by chemical reaction. Strictly speaking, they are not energy sources. Catalysts are effective, because they permit the paint chemicals to react more rapidly at any given temperature than they normally would. Thus, curing can be achieved more quickly at the same temperature or in the same time at a lower temperature. This can be important when coating heat sensitive materials such as thermoplastics or when fuel conservation is important.

## 9.8 HEAT RECOVERY

A well-designed cure oven will not exhaust enough Btu's to make it cost effective to install a heat exchanger for heat recovery. The volume of exhaust is based on the amount of gases that must be removed from the oven interior to maintain a safe environment. Since the exhaust is gas laden, it is not possible to use the heated air without a heat exchanger. A good heat exchanger is expensive and the efficiency will be around 75%.

The stack gas temperature must be maintained above the dew point to avoid condensation in the stack. This limits the amount of energy that can be recovered from the stack gas. With the cost of the heat exchanger, duct and fan for recovery, limits on how much energy can be recovered, and limited efficiency, it does not make sense to recover heat from an oven.

If volatile organic compound (VOC) abatement equipment is necessary, heat recovery through the use of a secondary heat exchanger may be worthwhile because of the high temperature used in a thermal oxidizer. The recovered heat can be used for a boiler, hot oil heater, or heated stages of a pretreatment washer.

## 9.9 SUMMARY

A properly designed oven will have easy access and maintenance features such as platforms, ladders, access doors, lights, and so forth. Providing good access and maintenance features will help ensure proper maintenance, which will keep rejects to a minimum, prevent unexpected shut-down, and provide maximum operating efficiency.

Convection heating is slow, but it is still the most dependable and flexible method of curing an organic coating. The use of IR or other means of accelerating the cure process should be carefully tested before a commitment is made. The burner used for a convection oven should be a modulating-type burner with a wide turndown ratio to provide the best possible efficiency.

The oven size should never be too short; a longer process time can be managed by reducing the oven temperature, but, if the oven is too small, no reasonable solutions are available, particularly if production increases necessitate an increase in line speed.

# 10 Testing Paint Materials

## 10.1 INTRODUCTION

Testing is an important part of the operation of a paint system. Testing is done to monitor the system and to confirm that the finish meets established quality standards and the expectations of the customer. The end use of a painted product should determine what tests are important.

The incoming paint material is sometimes tested to confirm that the color and gloss are correct and the paint is free of defects. In some cases, the paint supplier will certify that the paint they are providing meets all required physical properties.

The paint should also be tested to confirm that it is ready to spray. Some sprayed sample panels can be used to confirm this before the paint is put into production. Viscosity, a measurement of the flow characteristics of the paint, should always be tested before using a fresh batch of coating.

## 10.2 PAINT VISCOSITY

Viscosity is a very important paint property, usually determined by measuring the time required for a given quantity of paint to flow through a hole in the bottom of a metal cup. A number of cup sizes and drain hole diameters are available for use with different viscosity paints. Three widely used viscosity cups are the Fisher, Ford, and Zahn viscometer. Table 10.1 gives conversion values for use with these cups.

It is important to correct the viscosity cup flow-out times for the temperature of the paint. The recommended spray viscosity is typically based on a temperature of 70°F. If the viscosity is measured at a colder or warmer temperature, the actual viscosity could be too low or too high. A paint supplier can provide the appropriate corrections for their product. Be sure that the type of Zahn cup or other viscosity cup used is consistent. In addition, be sure that the method of measurement is consistent. Some operators consider the first break in the paint to be the stop point, while others may wait until the cup is virtually empty.

## 10.3 FINISHED FILM TESTING

Finished film testing is used to confirm physical properties of the coating after it is applied and cured. Daily tests might include such things as gloss, color, hardness, and adhesion. The particular tests used depend on the properties that the coating is supposed to provide and the established quality standards.

**TABLE 10.1**
**Conversion Chart for Commonly Used Viscosity Cups**

| Fisher #2 | Ford #3 | Ford #4 | Zahn #1 | Zahn #2 | Zahn #3 |
|---|---|---|---|---|---|
| | | 5 s | 30 s | 16 s | |
| | | 8 | 34 | 17 | |
| 15 s | 12 s | 10 | 37 | 18 | |
| 17 | 15 | 12 | 41 | 19 | |
| 18 | 19 | 14 | 44 | 20 | |
| 21 | 25 | 18 | 52 | 22 | |
| 29 | 33 | 25 | 68 | 24 | |
| 33 | 36 | 28 | | 30 | |
| 39 | 41 | 31 | | 34 | |
| 44 | 45 | 32 | | 37 | 10 s |
| 50 | 50 | 34 | | 41 | 12 |
| 62 | 58 | 41 | | 49 | 14 |
| | 66 | 45 | | 58 | 16 |
| | | 50 | | 66 | 18 |
| | | 54 | | 74 | 20 |
| | | 58 | | 82 | 23 |

Finishing tests are an important task in confirming that the finish meets the standards and can provide the necessary performance characteristics.

### 10.3.1 PAINT TEST STANDARDS

Most of the finished film tests used by industrial painters are based on the American Society for Testing Materials (ASTM) international standards (originally known as the American Standards for Testing and Materials). ASTM has several publications that provide the test methods and how to interpret the results. Some performance tests are based on other sources such as the American Architectural Manufacturers Association (AAMA) or European standards.

It is important to have a precise test method and consistent standard to provide meaningful data and consistent results. A good test method describes how the test panel will be prepared, how the test will be conducted, and how the results will be reported. If the test frequency is too random or the test methods are inconsistent, the results will not be as useful.

### 10.3.2 TYPES OF TESTS

There are standard tests that cover most properties of the finished film that are relatively simple to do as part of a daily operation. Some of the more complicated tests, or tests that involve expensive, specialized equipment, can be conducted by testing labs.

Tests can also be created that will help to determine if the part will meet a particular real-world condition. For example, if the part will be subjected to brake fluid, then a chemical test that subjects it to brake fluid is useful.

#### 10.3.2.1 Film Thickness

The thickness of a dry paint film is important to the performance of the coating. Thin films may appear to be the wrong color, or they may not provide the necessary level of performance. Water can more easily penetrate to the substrate if the film is too thin. Thick films can be a problem too. Thicker films are more likely to crack in use or they may create problems when two mating parts must be fitted together.

Wet-film thickness is measured for process control. It can be measured with a handheld immersion gauge that has a series of teeth along the edge of different lengths. The gauge is placed on the freshly painted surface, and the edge of the gauge is supported by two teeth of the same length for measurement control. All the other teeth are different in length and shorter than the control teeth. The wet thickness is measured as the last tooth that leaves a mark in the paint film. Therefore, if the wet gauge reads 3 mil and the coating is 50% solids, then the dry-film will be about 1.5 mil. This is a rough method of predicting the final dry-film thickness, but it does give the painter an indication of whether or not he/she is applying the correct amount of paint without waiting until parts come out of the oven. This method of measuring leaves marks in the paint, requiring the part to be reworked.

The dry film thickness of paint on iron or steel surfaces is easily determined with a pull-off gauge. Pull-off gauges reflect the force required to pull a magnet suspended on a spring inside a metal case away from the painted surface. The force will decrease as the paint thickness increases, because the paint keeps the magnet further away from the metal. Pull-off gauges may be graduated in microns, mil (thousandths of an inch), or arbitrary units. They are direct measurement devices.

Dry-film thickness can be measured much more accurately with an electronic instrument. If the base material is metallic, a device is used that measures the strength of eddy currents induced in the metal by a probe containing a conducting coil. The strength of the eddy currents decreases as the paint thickness increases. The read-out meter for eddy current strength can be graduated in any desired thickness units.

If the dry paint is on a nonmetallic surface, film thickness can be measured with a beta ray back scattering gauge. This instrument emits low-energy radiation in the form of beta rays (electrons) that pass through the paint and are reflected by the more dense material beneath it. The quantity of beta rays that are reflected back to the gauge decreases as the film thickness increases. These gauges also work when the painted surface is metallic.

Dry-film thickness on nonmetallic surfaces is sometimes determined by cutting a “V” shaped trough through the paint and measuring the width of the cut at the top of the trough. A thicker film will produce a wider “V” at the top. A low-power magnifying glass with internal calibrations is often used to make this measurement. It may be calibrated directly in thickness units.

### 10.3.2.2 Film Hardness

The hardness of the paint film is important, because it is related to brittleness and water permeability. Films that have been over-cured or under-cured can often be detected by hardness testing. Pencil hardness and indentation hardness are two widely used testing techniques.

Pencil hardness tests measure resistance to indentation by a series of increasingly hard pencils that have been sharpened to a chisel point. The higher the hardness of the pencil lead required to make a gouge into the paint, the harder the film.

Indentation hardness testers measure film penetration, in a specified time, by a metal tip under certain mechanical loading conditions. The time factor is important, since many paints deform gradually under load.

### 10.3.2.3 Impact Resistance

Resistance to impact damage (chipping and cracking) is an important property for nearly every paint film. It is difficult to have both high impact resistance and high hardness. This is because impact energy is best absorbed when the film is softer and able to deform upon impact. However, hardness is desirable, because it normally means better gloss retention and weatherability. Most paints are formulated with a compromise between hardness and impact resistance.

Impact resistance testing usually involves striking a painted panel with a hard object, such as a steel ball or hammer and measuring the indentation that results. Another test (Society of Automotive Engineers Test Procedure V400) is called a gravel damage test. The gravel damage test uses stones hurled against the panel to inflict damage.

The most common way to measure impact resistance is ASTM D 2794-93. A standard weight is dropped from a height onto a coated panel. The indentation is inspected to detect if the coating has cracked. The weight can be dropped from different heights, and the results are then measured in inch-pounds. The goal is to see how many inch-pounds the coating can take without cracking.

### 10.3.2.4 Tape Adhesion

Adhesion of a paint film to its substrate is often measured by jerking the paint away from a scribed "X" or grid with a strip of tape. Three M Company's #600 Crystal brand transparent tape or another tape with strong adhesive properties will work for this test. The tape is jerked back upon itself as nearly in the plane of the painted surface as possible. A numerical rating system from a 0 for total failure to a 5 for 100% adhesion with no loss may be used to evaluate tape adhesion test results. If a scribed grid has been used, the failure of adhesion may be expressed as the percentage of squares that have some loss of paint (D 3359-97).

A more severe test of adhesion is sometimes used on aluminum substrates. The standard ASTM D 3359 test is used, but the crosshatch pattern is subjected to boiling demineralized water for 20 min before being tested with the tape pull. This test, AAMA 2604, 7.4.1.2, is useful on aluminum substrates that will be used in an outdoor environment where the paint film will be subjected to water permeability and possible oxidation under the film.

### 10.3.2.5 Humidity Testing

Water vapor is one of the most severe agents to which a paint film is exposed. Because water molecules are small and binder molecules are constantly vibrating, moisture can easily penetrate lightly pigmented paints. Water also penetrates heavily pigmented primer films, although at a much slower rate.

Moisture in a paint film can be warmed by sunlight or other sources of energy. When warmed, it will tend to vaporize and exert a pressure that causes the film to swell. If the film is flexible or if the water occurs near a spot of grease or salt crystal under the paint, the swelling will be more severe, possibly causing adhesion failure or discoloration of the film.

The condensing humidity test is widely used to measure humidity resistance. In this test, water vapor is allowed to condense on sample panels. The condensed water drips off the panel and is revaporized by means of an evaporative heater in the bottom of the test chamber. A typical test involves water at 60°C (140°F) for 24 h. After testing, panels are checked for blistering, color changes, and loss of gloss.

Another humidity test involves exposing the panels to 100% relative humidity at 38°C (100°F) for 24 h.

Neither of these tests can provide service life predictions. However, they are useful for determining the best paint from a series of formulations.

### 10.3.2.6 Salt Spray Testing

The use of salt solution spray testing is an attempt to accelerate the corrosion process and cause early paint failure. Panels are usually exposed for up to 14 days to a mist of 5% (w/v) sodium chloride solution at 33–36°C (92–97°F). The mist is produced by blowing hot saturated air through a 5% salt solution.

The panels are evaluated for two types of corrosion:

1. *Rust-through*—the percentage of the surface, which has rust visible through the paint
2. *"Creep"*—the distance in 1/32 of an inch (0.8 mm) from the center of the scribe line that the paint film breaks down and separates from the substrate

The results are measured on scale with a predetermined point described as failure in number of hours of exposure. Sometimes, acetic acid is added to the salt spray solution to accelerate the corrosion.

Salt spray testing has been used as a standard for performance by many coaters from all different types of industry. It is poorly understood and not necessarily reliable as a predictor of field service. The most important value of salt spray testing is comparison of different pretreatment methods and coatings to see what appears to be the best combination for corrosion resistance. In all cases, the salt spray comparison should be done with the same steel panels and the same test cabinet.

One weakness with the results of a salt spray test is the substrate itself. Steel quality varies substantially and the failure in the salt spray test may be due to poor steel, not pretreatment or the paint film. For this reason, it is very important to always run standard q-panels as a control.

Another factor to consider when evaluating the pretreatment or paint film is the cure cycle. If the paint film is not fully cured, it can cause failure in the salt spray test that may be blamed on the pretreatment process or the paint. The cure of the film should be confirmed before the panels are tested in salt spray.

### 10.3.2.7 QUV Testing

A Q-LAB Ultraviolet (QUV) test chamber reproduces the damage caused by sunlight, rain, and dew. Coated parts or test panels are placed inside the chamber and subjected to alternating cycles of light and moisture at controlled, elevated temperatures.

Parts can be measured for resistance to chalking, fading, color fastness, cracking, blistering, embrittlement, strength loss, and oxidation.

The QUV test chamber provides a more accurate comparison of different processes and materials than salt spray testing alone. It is more helpful in evaluating the affect of outdoor exposure on different coating materials and a somewhat better predictor of actual field life.

### 10.3.2.8 Outdoor Exposure

Outdoor exposure tests are slow, but they are the best way to predict weatherability. Three months of exposure takes a while, but it does provide good information about how well the paint film will last in an outdoor environment. Long-term exposure is not very useful for solving transient production problems, but it is a good way to qualify a paint material for use in the sun.

The most common defects turned up by exposure testing are fading, cracking, checking, chalking, blistering, and peeling. Often a portion of the panel is buffed after testing to see to what extent the original appearance can be restored.

Exposure tests are usually conducted in a sunny climate such as Florida or Arizona to get the maximum ultraviolet radiation effect. Panels are usually exposed 5° from the horizontal, facing south. Florida is a preferred location in this country because of the sudden and frequent humidity changes that occur there. The test panel is held in a clamp that shields the top portion of the panel from exposure. Mirrors and mechanical devices are sometimes used to accelerate the exposure and produce earlier results.

### 10.3.2.9 Temperature–Humidity Testing

Temperature changes, especially if they are rapid, present a severe challenge to paint films. Cracking is the most common failure related to temperature change. The film fails because of stress that develops when pigments, binders, additives, water vapor, and micro-air bubbles in the film expand and contract at different rates as the temperature changes. Since expansion coefficients for trapped air, water vapor, pigments, and other paint components may be quite different, large internal stresses can develop at various locations within the film. The stress created in the film can cause it to crack.

A typical temperature–humidity test cycle is

- 24 h at 38°C (100°F) and 100% relative humidity
- 20 h at –23°C (–10°F)
- 4 h at ambient temperature

This cycle is often repeated 12–15 times. The panel is rated by evaluating the percent of the surface area that has cracked.

### 10.3.2.10 Rinse Blistering

A rinse blister test helps to expose any unreacted salts left on the surface after evaporation of a water rinse. The process water is applied as droplets to a panel and allowed to dry. After the droplets have dried, the panel is top-coated and subjected to humidity testing. Blisters often occur where water-soluble salts have been left from the droplets. This is because moisture from the humidity chamber moves through the topcoat, collects around the salt crystals, dissolves them, and exerts a swelling pressure against the overlying film. Panels are usually evaluated against a control after 24, 48, and 96 h. Sometimes a tape adhesion test is also run without a scribe pattern being cut in the film.

### 10.3.2.11 Corrosion Cycling

Paint films in use are always exposed to a number of cyclic environmental factors. A corrosion cycle test measures the behavior of a film under a combination of test conditions.

Usually, a combination of salt, humidity, and changing temperature is used for corrosion cycle testing. A typical sequence is listed below:

- 4 h at 5% neutral salt spray
- 18 h at 38°C (100°F) 100% relative humidity
- 2 h at –23°C (–10°F)

The resulting panels are rated against a control on the basis of the percent of rusted area. Cycle testing can be a more accurate way of predicting comparative qualities of coatings than salt spray alone.

### 10.3.2.12 Color Matching

Color matching is a very important step in the process of manufacturing. Colors must be consistent so that the product is identical and recognizable from part to part. In addition, many products have multiple components, sometimes with different substrates, and each component must be the same color.

Color match can be difficult at times because of human variability in color perception. Two panels that appear to be the same color to one person may seem dissimilar to someone else. A color may also change when viewed under different lighting, fluorescent versus outdoor light, for instance.

Usually, colors are compared under constant conditions of illumination and background. Two light sources are often used to examine the panel, one predominantly blue and one predominantly yellow. The important thing is that the paint buyer and seller mutually agree upon color standards and comparison methods. If standardized color chips are used, they should be stored in the dark to minimize fading.

Elaborate and expensive color measuring equipment is available for analyzing the color composition of a painted surface. These devices are used in paint formulation laboratories. They are generally not of value in a production situation.

#### 10.3.2.13 Gloss

The amount of light reflected to the viewer's eye determines the gloss of a paint film. More reflection of light will appear as higher gloss. It is the smoothness of the surface that affects the reflection of light. The smoother the surface, the better the incident light can be reflected toward a viewer without scattering.

Gloss is often measured with a photoelectric device. The light reflected is converted to an electric signal by a phototube. The strength of the signal is proportional to the amount of light reflected. This reflected light, when compared to the original light falling on the surface, is a measure of gloss. There are a number of test variations. The angle of reflection may be 20°, 45°, 60°, 90°, or some other value. Usually, the gloss value is compared with a previously established standard.

# 11 Quality Control

## 11.1 INTRODUCTION

Some coatings are applied to products for temporary protection or to provide a temporary coating of some acceptable level. For example, oil filter canisters are coated with paint or powder coating at the factory, but once the filter is installed in the car, the owner has little concern about the appearance or performance of the coating.

Most coatings are put on to provide a long-lasting and attractive finish. The quality of the finish is affected by every step of the paint process. With the correct coating material, appropriate pretreatment system, good application equipment, and the proper curing system, it is possible to turn out a consistent finish with the desired quality.

Still, even the best systems sometimes do not always produce a perfect finish. One problem is that the paint process has both mechanical elements and chemical elements that must be controlled. Manufacturers are often skilled and committed to the control of mechanical variables such as line speed, but they are not always committed or prepared to control the paint material for spraying or able to figure out why the paint is not performing correctly. There are more complex variables that must be controlled with a chemical process and they can be just slightly out of range and create severe defects.

## 11.2 PROCESS CONTROL

A consistent, high-quality finish is directly related to degree of control over the process and a commitment to keeping all parameters in balance at all times. Careful monitoring and process control measures are needed to monitor and adjust the operating parameters of the system. In order to do this successfully, the variables of the process must be understood.

### 11.2.1 SCHEDULING

The first step to be controlled is the scheduling of parts and colors to be painted. The longer the run of a particular part and a particular color, the more efficiently the paint line will run. Of course, the pressure of market demands and the need for just-in-time (JIT) production makes it difficult to group parts and colors together. Still, every effort should be made to schedule groups of colors and parts as much as possible to reduce waste and maximize output.

### 11.2.2 RACKING

The next area of concern is loading and racking. Proper rack design is necessary for getting a quality finish. If the parts are not presented properly to the application equipment, it can cause film defects such as blistering and runs. Alternatively, the opposite can occur, light paint areas where the substrate shows through. In either case, the result is rejected parts that must be repaired and repainted. Rack design is an art and science in itself. Good racking is essential for film build control, high first pass yield, and good transfer efficiency.

The paint rack is a tool and should be treated as an important part of the process. Parts should be hung as precisely as possible and in consistent position with good exposure to the spray equipment. The available product window should be filled as much as possible in the vertical and horizontal dimensions.

Parts need to be hung correctly on the rack. This should be simple, but it is not uncommon to see parts hanging at odd angles or hooks that have no part on them at all. It is important that a written or visual procedure be available at the loading area so that the workers who are hanging parts can refer to it to see the correct part positions. Since the people loading parts on the line will handle every part, they can also inspect the parts to make sure there are no obvious substrate defects that would cause painted parts to be rejected. By catching faults such as misshapen parts, metal gouges, deep scratches, and so forth, the cost of painting bad parts can be avoided.

Good racking is especially important when robots are used. The robot will not adjust for a part that is not in the proper position so the precise application that a robot can deliver is lost, if the part is not in the right position. Tooling for robotic painting must be more precise than racks used with other application equipment.

### 11.2.3 PRETREATMENT

Pretreatment is one of the most important steps in getting a quality finish. The steps in the pretreatment process are recommended by a qualified pretreatment chemistry expert. They will evaluate the soils on the part and the substrates to be run and determine what chemistries will work best to meet a particular quality standard. At a certain line speed with a certain density of product going through the pretreatment stage, the chemical supplier will recommend the proper chemicals, concentrations, and temperatures of the various solutions used to obtain a clean and properly treated part.

The chemical supplier will also develop a schedule of tests to ensure that the proper concentration of chemicals is maintained. They can also provide tests that will determine the amount of carry over of chemicals into the rinse tanks and the amount of fresh water make-up required to ensure proper rinsing. All testing should be recorded on work sheets so that if there is a problem, the actual test values may be checked to see if the problem is related to pretreatment.

Mechanical maintenance of the washer is also critical to successful cleaning and treatment. Each section of a power washer should be checked on a regular basis to be sure that all the nozzles are spraying properly and in the right direction. If nozzles are not working or if they are misdirected, there is potential for improper pretreatment.

Parts that are not cleaned, phosphated, or rinsed properly can produce immediate paint rejects or failures that occur in the field.

Besides monitoring the chemicals and rinses on a daily basis, parts should be examined as they come out of the spray washer before they go into the dry-off oven. At that point, the water should be sheeting off with no beads of water remaining on the part. Beaded water or water spots indicate something present on the surface of the part that is not letting the water run off. If water is beading up on the surface, it indicates a soil that has not been removed. Soils left on the part surface can lead to adhesion failure of the paint to the substrate or premature corrosion.

The line speed that the system was designed to operate at sets up the critical contact times inside the stages of the washer. If the pretreatment system is designed to give optimum cleaning, phosphating, and rinsing at a line speed of 10 ft/min and the speed is increased to 15 ft/min, the pretreatment time has been reduced by one-third. More carryover and faster dilution of the chemistry will occur, and the rinses will be contaminated more quickly. With higher throughput and less time of exposure, the treatment process may not be effective.

Slower line speeds can cause problems too. Excess phosphate coating can leave a powder residue on the part or cause flash rusting. Both these problems will cause a lack of adhesion and reduce moisture resistance. If the line speed needs to be changed then the system will need to be adjusted to the new line speed.

A lot of these problems can be spotted before they are painted. Parts coming out of the dry-off oven should show an even color of phosphate, plus no mineral deposits and no powder buildup. A clean dry part should not yield dirt, oil, or powder when it is wiped with a clean cloth after it comes out of the dry-off oven.

Some older paint lines may have pretreatment systems that provide marginal cleaning and treatment results. They may have been built for coatings with low solids, high solvent content or for a lower quality standard. The high solvent content in these materials could help to wet out soils on the surface, and the long-chain resins could bridge minor problem areas and give good adhesion. High-solids, low-solvent paints will not tolerate poor cleaning. The solvent level is very low, and in many cases, the solvents used are not aggressive enough to tolerate even small amounts of oil or other soils. The short-chain resins need more uniform sites to ensure good paint adhesion. Older systems may need upgrading to accommodate newer paint technologies.

### 11.2.4 DRY-OFF OVENS

After leaving the pretreatment section, parts are usually run through a dry-off oven to remove the water from the parts. If parts have areas where water is cupped, the puddles should be removed by the use of air. Boiling out the puddles with heat is expensive and can cause mineral deposits on the part surface. Air can be blown onto the part from the dry-off oven discharge duct or from a high velocity blow-off, or both. Some puddles of moisture may require a manual blow-off operation, because the water is not accessible to any other method. Proper racking to ensure good drainage is also important.

## 11.2.5 COOL DOWN

When the parts exit the dry-off oven, they will be very hot. The parts can be cooled by time (length of conveyor) or forced-air cool downing. If a textured or orange peel look is desired, then a hot part will allow the solvents to evaporate more quickly and cause less flow. If a smooth finish is required, the part must be close to ambient temperature.

## 11.2.6 PAINT APPLICATION

### 11.2.6.1 Spray Gun Adjustment

There are some basic spray principles that should be reviewed to understand how the paint will behave when it is sprayed. Control of droplet size affects the deposition and flow of the paint. Droplet size affects solvent evaporation and influences paint flow-out on the surface. Since many wet paint defects are related to paint flow-out, the ability to control droplet size is important.

Delivery and atomization of the paint play a key role in droplet size. The ratio of fluid pressure to atomizing pressure affects the break up of the paint. The fluid viscosity of the paint and the balance of fluid pressure to atomizing pressure will influence the droplet size. The droplet size can be decreased with added air pressure or reduced paint pressure. An increase in atomizing pressure will move the paint at a higher velocity and may cause more overspray. A decrease in fluid pressure will reduce the amount of paint delivery and may cause coverage problems. Which control to adjust depends on what adjustment will work best in a given situation, more air velocity or less paint.

The relationship between droplet size and fluid flow is best understood by considering the relationship between the size of the droplets and their total surface area. In Table 11.1, a droplet has been divided into two and then into four smaller droplets. The total surface area increases as the droplets get smaller.

If a known volume of paint is divided into more droplets, it will cover more surface area. The larger total surface area allows more solvent loss while the paint is airborne and the droplet strikes the work in a drier, less runny state.

Droplet size has little effect on film thickness. Thickness is primarily determined by the paint pressure, gun speed, gun-to-part distance, and number of passes. Changes in any of these variables can lead to wet films that are too fluid due to retained solvent. The effect of these parameters on paint flow-out is indicated in Table 11.2.

**TABLE 11.1**
**Ratio of Droplet Size to Total Surface Area**

| Number of Droplets | 1 | 2 | 4 |
|---|---|---|---|
| Droplet size (volume) | 1 unit | 1 unit | 1 unit |
| Total surface area | 1 unit | 1.2 units | 1.4 units |

**TABLE 11.2**
**How Adjustment of Application Variable Affects the Fluidity**

| Increasing | Effect on Fluidity |
|---|---|
| Air pressure | Decrease |
| Gun speed | Decrease |
| Gun distance | Decrease |
| Paint temperature | Decrease |
| Part temperature | Decrease |
| Solvent evaporation | Decrease |
| Paint pressure | Increase |
| Orifice diameter | Increase |
| Line speed | Increase |

Note: All other variables held constant.

For hand spray operations, it is important to make sure that there is enough time to perform trials and develop the correct painting pattern. Manual spray gun adjustment and spray patterns should be as consistent as possible.

Automatic application should be closely monitored to make sure that the guns are clean, well maintained, and working properly at all times.

When automatic equipment is used with hand reinforcement, a decision must be made on where to locate the manual stations, before or after application by the automatic equipment. The manual operator can clearly see the areas where reinforcement is needed, so it may be best to locate the automatics first. If the manual spray is located before the automatics, the painter will tend to cover more area, because the entire part is bare. However, if the painters are well trained and know exactly what areas to reinforce, the best finish results may be obtained by applying the manual coverage first. The high-speed turbo bells or disks shear the paint more, causing a smoother finish and blending the lines from manual to automatic more uniformly.

In some cases, there will be a very slight visual difference in color and texture of manually sprayed areas versus automatically sprayed areas. In cases where hand reinforcement is after the application by the automatic bells or disks, the touch-up painters may literally repaint the whole part so that the paint appearance is consistent. Testing and training are the key elements to avoid mistakes in this area.

The lead time (guns are triggered before the part is in front of the spray pattern) and the lag time (guns remain on after the part passes out of the spray pattern) on the automatic equipment should be checked daily to make sure they are correct. If the lead starts too soon, it may cause buildup and possibly cause runs or blisters on the lead corner. If the lead starts too late, it may cause light paint and improper electrostatic wrap on the part. If the guns shut off too soon, there will be light coat areas on the parts, and if they run too long, it is a waste of paint and may cause fatty edges.

The automatic equipment should do as much of the painting as possible, since it is the most consistent painter. However, automatic guns do not have multiaxis motion unless they are mounted on a robotic arm, so penetration in angles or deep recesses is somewhat limited. Increasing the flow rate to get more depth of coverage may increase the film build on flatter, more accessible surfaces. Automatic application should be limited to the surfaces where uniform film build is possible and not forced to cover areas that are hard to reach.

Once the automatic spray guns and hand spray pressures have been properly set to give the desired finish at the desired film build, the settings should be recorded for each part and used by all painters for set up and control. If the settings need to be changed, it may indicate that some other process variable is out of control range. Worn equipment, a change of paint material, plugged hoses, or some other problem may be affecting the gun settings.

The correct air pressure is very important. If the air pressure is too low, it can cause poor paint break-up and give a rough orange peel look. It will increase the tendency for the paint to blister because of heavier film build. Higher air pressure will provide improved atomization and a smoother finish, but excess pressure may blow more paint past the parts.

The fluid pressure determines the amount of paint delivered to the parts, and an adjustment to the fluid pressure has a direct correlation to the amount of film buildup. With bells, the settings for the shaping air should also be recorded and checked to make sure that the pattern is set up correctly for the part surface. A record of spray gun settings should be logged for troubleshooting if something goes wrong.

### 11.2.7 PAINT MATERIAL

The paint material is another critical variable that must be controlled. If the paint is at the same temperature and same viscosity every day, then it should apply the same way every day. This is very important since the viscosity of high-solids coatings changes very dramatically with temperature.

A paint that is 18 s viscosity on a #3 Zahn cup at 72°F may be 32 s viscosity on the same cup at 64°F. If a paint line technician is unaware of the paint temperature, they may further reduce the paint with solvent to achieve the desired viscosity. This will over-reduce the paint, which can then cause runs, sags, and blisters. The operator thinks that the paint is the same as it was yesterday, but the viscosity is different.

The paint supplier normally supplies the paint at a certain viscosity based on a temperature of 77°F. For many production environments, it is not feasible to measure viscosity at that temperature. It is important to use a consistent temperature for measuring the viscosity of paint. Each material has particular spray viscosity at a particular temperature that works well. The viscosity of the paint should be checked every time it is used. This will show if there has been a lot of solvent evaporation or if the solvents have swelled the resin and caused the paint to thicken.

A radical change in paint viscosity can indicate that paint break down is occurring or something may have been added by mistake. If paint line heaters are being used, the temperature of the paint at the end of the gun should be checked to make sure that the heaters are working correctly and the paint is at the desired temperature. If the paint is at too high a temperature, it may cause runs and sags. If the paint is too cool, it will be more resistant to atomization and that could lead to heavy paint buildup that could cause blistering. It would also tend to give more orange peel to the finish.

### 11.2.8 FLASH-OFF

After the paint has been applied, the solvents begin to evaporate from wet film. A flash-off area follows application to provide time for the solvents to evaporate, and the paint film begins to flow and smooth out. If the flash-off time is too hot, the surface of the film may begin to form before the solvent can leave and cause blistering. If the flash-off area is too short or cold, the solvents may not be fully flashed when the part reaches the next coat or the cure oven. Best results are obtained where the ambient temperature is kept fairly constant. In some cases, it may be slightly elevated to help with the evolution of the solvents. Flash time and temperature are based on the paint material being applied and the film thickness as recommended by the supplier.

### 11.2.9 CURING

The final step in the paint application process is the cure of the paint film. In most painting operations, an oven of some sort is used either to cure or to accelerate drying. There are systems that cure with the use of ultra violet rays, electron beam, moisture, and induction. These coatings are very important but not as commonly used as thermal reactive or air-dry products. Ovens for thermal cure include convection, infrared, and combination infrared/convection. The exact oven to use is based on the type of paint, the available space, parts to be painted, finish desired, available capital, and volumes. In general, gas-fired convection ovens are the most dependable and flexible. They use heated air to raise the substrate temperature so that the coating will cure from contact with the hot surface.

Oven balance is important for accurate and complete cure. A temperature-recording device, such as a Datapaq system, is used to measure the air and part temperature in the oven and create a time/temperature profile. The chart shows whether or not the part temperature was high enough for enough time to reach full cure (Figure 11.1).

If the profile shows that the part does not reach sufficient temperature for the minimum cure time, then the paint film will be under-cured. An under-cured film will not adhere properly or perform properly. If the profile shows that the part exceeded the cure time and/or temperature, it may be fine. Most paint materials will tolerate a certain amount of extra cure. However, it is possible to overcure the coating and cause the paint to turn brittle, discolor, loss of gloss, or other film properties.

Some companies run a temperature chart through their ovens every day. That may not be necessary, but once a week or a month is good practice for process control. If the line speed is changed, a temperature profile should be run at the new line speed to make sure that the cure cycle is within the specified guidelines. If the gauge of the metal being painted varies quite a bit, then it will probably be necessary to change the oven temperature settings or line speed to get a proper cure on the various parts.

### 11.2.10 RECORD KEEPING

A record of the oven temperature setting and line speed for each part should be made, and that information should be readily available for the paint line operators. A running record of the paint line conditions should be made as each different part is painted. A single form can be used to record the conditions of the system, or separate forms can be used for each component of the operation.

By keeping careful records and using the recorded information for process control, the results will be more consistent. If careful records are maintained, variations in the finish coat should be traceable and corrections can be made. There is a natural tendency to gradually relax rules for accurate record keeping, because everything is going well. To keep things running at peak performance, diligent record keeping is a must.

## 11.3 PAINT FILM DEFECTS

The causes of defects in a paint operation are too numerous to list and although all coaters attempt to eliminate them, it is very difficult and costly to cut defects to zero. Knowing some common causes of defects and implementing a good process control program will keep the number of defects to a minimum.

Some causes of paint defects are harder to identify and correct than others. Some of the common problems with paint films are associated with material and process problems. Defects can be controlled through better understanding of the process variables associated with surface preparation, paint material control, application, and cure.

### 11.3.1 PRODUCTION DEFECTS

Avoiding defects is a function of understanding the variables that affect the process, measuring them, and controlling them. When defects do occur, it is important to identify the cause and make adjustments to prevent additional rejects.

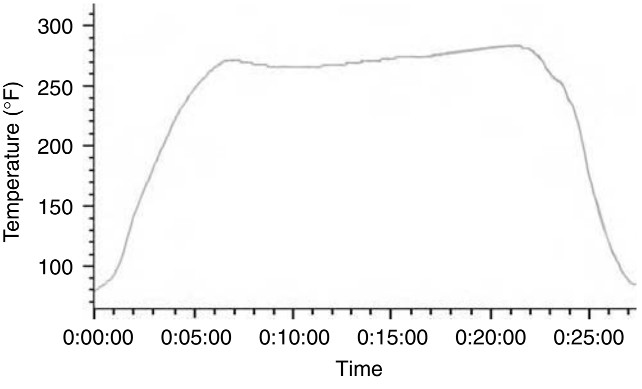


**FIGURE 11.1** Temperature graph from cure oven.

#### 11.3.1.1 Orange Peel

Orange peel is a textured effect that resembles the skin of an orange. The paint will usually feel smooth but will appear to have small depressions when viewed at an angle to the light. Orange peel often results when the paint droplets are properly atomized. If they are not fluid enough to flow together smoothly on the surface, the film will be somewhat textured. Orange peel is also affected by excess film thickness or paint that is not sufficiently atomized. A thicker wet coat may not flow out as smoothly.

Orange peel may also be caused by uneven shrinkage as the paint loses solvent and begins to cross-link. A certain amount of orange peel is nearly always found with enamels. Sometimes a textured surface beneath the paint will result in orange peel.

Orange peel can often be reduced or eliminated by adjustment of the atomizing air pressure to achieve the proper droplet size. Adjustment of the gun-to-target distance can accomplish the same thing.

#### 11.3.1.2 Sagging

Sagging occurs when there is too much wet film applied. Paint will sag whenever gravity overcomes the internal flow resistance of the film. This occurs when the paint contains too much solvent or is applied too thickly.

Possible cures for sagging include

- Increase the air pressure
- Decrease the paint pressure
- Move the gun more rapidly
- Increase the gun-to-part distance
- Use faster solvents
- Use multiple coats of paint

These changes are designed to give better atomization (drier paint) or result in a thinner wet film.

#### 11.3.1.3 Flooding, Floating, and Mottle

These terms, while describing technically different defects, are often used interchangeably. They refer to a separation of pigments within the paint film. If the heavyweight pigments come to rest in a different position than the lightweight pigments, the film will have a dappled appearance (mottle). The pigments may separate by sinking or floating, or because there are whirlpool-like currents set up in the wet film by evaporation. The heavier pigments are thrown to the outside of these whirlpools while the lighter pigment particles remain nearer the center. As solvent evaporation continues, the paint becomes more and more viscous, finally trapping the pigments in a fixed position.

Mottle is more noticeable with some colors than with others. Paints containing organic pigments and high levels of aluminum flake are especially likely to mottle, because the flakes tend to float near the center while the dense color particles are likely to be spun to the outside of the whirlpools. The mottle-spots may be as large as 6 mm (0.25 in.) in diameter, although they are usually much smaller.

The pigments do not separate to give the mottled effect unless the paint remains fluid for too long a time. Extra-thick films (more total solvent) or films with insufficient solids are more likely to have this problem.

Corrective adjustments for mottling are

- Reduce film thickness
- Use a faster solvent
- Move the gun back
- Increase the flash-off time between wet coats

#### 11.3.1.4 Silking

The term "silking" describes the appearance of light or dark flow lines in a paint film. It occurs when pigment particles are unevenly distributed in the film. Silking often appears where the wet paint has drained away from holes or edges, especially after dipping. It can occur if there are adjacent areas of the paint that differ considerably in wet-film thickness. The effect is easily observed when stirring a paint that contains aluminum flake where the plate-like pigment particles tend to orient themselves in nonrandom patterns due to the stirring motion.

Silking can be reduced by making sure the solvent evaporates as quickly as possible and by avoiding excessive paint flow over the surface.

#### 11.3.1.5 Solvent Pop, Bubbles, Pinholes, and Craters

These terms, often used interchangeably, describe defects that arise when solvent is lost too rapidly from a wet paint film. More than one of these defects can be present on a part and they may be located anywhere or everywhere on the surface. These defects are usually caused by solvent vapors forming within the paint and rising to the surface. The rising vapor lifts the paint film and the paint may not recede to a smooth and continuous film. A bubble occurs when the solvent vapor seeps through the paint film skin without causing it to rupture. A crater results when the broken bubble retains its jagged edge.

Anything that makes the paint film too solvent-rich, too thin, or causes it to lose solvent too rapidly may result in pops, bubbles, pinholes, or craters (Figure 11.2). The factors that may cause these defects include

- Low air pressure
- High paint pressure
- Not enough flash-off time
- Slow line speed through the booth
- Too much wet-film build
- Short gun-to-work distance

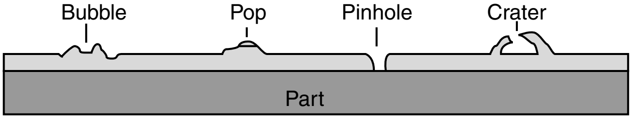


**FIGURE 11.2** Paint surface defects.

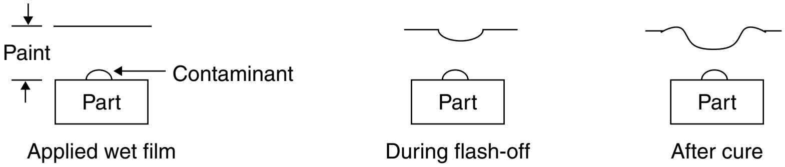


**FIGURE 11.3** Surface contamination.

- Slow gun speed
- Excess oven temperature early in the cure cycle

### 11.3.1.6 Fisheyes and Silicone Craters

Fisheyes are round depressions in the film. They vary in size from barely visible to more than 6 mm (0.25 in.) in diameter. Sometimes they are deep enough to reveal the bare substrate. Pigment sometimes gets collected in the fisheye giving it a dark center. They are caused by surface contamination that the paint cannot adhere to. As a result, the film forms around the contamination but not over it. A raised edge usually forms around the perimeter of the contaminant. Figure 11.3 shows how these defects can occur.

Fisheyes can be extremely frustrating, because it is so difficult to identify the cause. Paint flows away from the defect, because silicone or a similar oily substance acts like a lubricant. As it flows away from the contaminant, it creates a surface depression. If the repulsion is strong enough and the paint is very fluid, the depression may actually reach the surface. The idea of a liquid flowing away from a slippery substance can be understood by considering the behavior of water spread on a waxed surface.

Fisheyes are commonly caused by oil, grease, and silicone lubricants. Of these, silicones are the most likely source and the most troublesome, because they are so difficult to remove. Oil and grease can usually be removed by solvent wiping or hot alkaline cleaning. Silicones resist these and other cleaning techniques. Often, they must be sanded off, a risky operation since the chance of further contamination by the sanding dust is high.

Sometimes spraying as dry as possible (high air pressure) is helpful, because the paint will not flow as much. Fisheye-reducing products are commercially available. They are chemicals which, when placed in the paint, are absorbed by the silicone contaminant, changing its surface to one which is more paint-compatible, so the paint is less likely to flow and form a depression.

The best solution to a fisheye problem is to eliminate the source of the contaminant. Sources that can add silicone to a paint system include lubricants, mold release products, and aerosol spray products. If fisheyes are a persistent problem, an investigation will usually reveal the use of a silicone product in the plant.

#### 11.3.1.7 Overspray and Dry Spray

A rough, grainy surface is usually the result of dry-spray. This occurs when paint droplets have lost so much solvent in the air that they do not blend into the wet film on the painted part. Overspray is paint that originally missed the part and later settled on it (or another part).

To prevent overspray and dry spray, the air pressure can be reduced, the fluid pressure can be increased, the gun can be moved closer to the target, or the spray booth face-velocity can be reduced.

#### 11.3.1.8 Blushing

Blushing is a description of areas in the paint film that are "whitish" in color. It results from the condensation of moisture droplets in the wet film. The droplets condense from the air, because solvent evaporation lowers the air temperature below the dew point. Fast evaporating solvents should be avoided on humid days. The usual cure is to reduce the air pressure and/or add a slower evaporating solvent to the paint. A slightly elevated temperature in the flash area can help, and adequate exhaust in the flash area is important.

#### 11.3.1.9 Dirt and Contamination

Dirt on the surface of a painted part is a major concern for all painters, because it diminishes the appearance of the paint film. Dirt may come from the air around the spray environment, from the application equipment, or it may be in the paint. One of the first things to do in searching for the cause of a defect is to look at where it is on the part and where it is in the film.

If a defect is from dirty paint or manufacturing by-products that have not been removed by the cleaning process, it will usually be evenly distributed. If it is an external source, the defect will more likely be randomly distributed.

If the dirt is on the part surface, it was most likely there before the part was painted. If the paint application process involves multicoats, it is useful to determine what layer the dirt is in. It may be in a primer coat, a base coat, or a top coat, providing insight into the source of the dirt. Analysis by microscope can reveal the depth of the "dirt" in the coating.

If the dirt is in the paint material, it can be strained out. Dirt from ineffective pretreatment can usually be corrected by changes in the process or control of the pretreatment system. Soils that are on the part from the manufacturing process that cannot be removed by a spray washer can usually be tracked to the source and a change made to eliminate them. Air borne contaminants are the hardest to track and eliminate, because they can come from so many different sources.

High-solids paint formulas are less tolerant of dirt than more solvent-rich formulas are. The coating surface remains tacky, attracting, and holding dirt. Sources for this kind of air-borne dirt are so numerous that it is impossible to name them all. The list below will name some of the common sources.

- *People*—Air sampling of enclosed paint systems has shown that as much as 80% of the air-borne contamination came from the clothing, hair, and shoes of personnel.
- *Nature*—Pollen, road dust, and other outdoor dirt are sometimes brought into the plant through doors, windows, and unfiltered air supply systems.
- *The building*—Concrete floors may wear and give off dust.
- *Manufacturing*—Mechanical operations in the manufacturing process may generate dust, metal shavings, or wood dust.
- *Process equipment*—Conveyor, oven, washer, or other operations within the paint line can generate or concentrate dirt that will create a paint defect.

With all of these potential sources, the job of coating a part with no defects is a challenge to say the least. Here are some ways to help control dirt on painted parts. The level of dirt prevention that an operation adopts is directly related to their quality standards.

Restrict access to the paint area or clean room to essential personnel as much as possible. Have all entrants to the paint room put on nonlint paper suits, hairnets, and shoe covers.

Isolate the paint application area from the rest of the plant and supply filtered air to the enclosure that will create a slight positive pressure in the room to prevent air from infiltrating through the product openings.

Have the concrete floors sealed in the area where workers put on their paper suits and in the paint room. Build a vestibule at the entrance to the paint room and add deionizing air in the vestibule to neutralize the workers before they enter.

Clean all surfaces in the room as frequently as is necessary to avoid an accumulation of dust.

Use an inverted box track conveyor or sanitary pan under the conveyor. Use an automatic lubrication system with a dry-film, thin-film lubricant, and do not over-lubricate. Clean the conveyor and chain components regularly. If it will work with the product, a floor-mounted conveyor can help reduce dirt.

One of the keys in controlling dirt is to use good recording and tracking of dirt rejects. Fiber, metal shavings, paper, and dust are examples of types of contaminants. Rejected parts should be recorded and categorized by the type of defect. The source of the dirt should be tracked and eliminated. A microscope can be used to identify the nature of the dirt speck.

# 12 Cost Analysis for Finishing Systems

## 12.1 FACTORS THAT AFFECT COST

The operation of a paint system has many variables that affect cost. Effective control of these variables will provide the best quality at the lowest cost.

Some cost variables are part of the design, some are part of the operation, and others are related to decisions on how to run to the system. Each cost variable has to be considered to know how much the system costs to operate and how much to charge for painting a part.

### 12.1.1 System Design

The subject of how to design a paint system is long and could fill a book of its own. There are a few guidelines that can help with the sizing and equipment selection that are mostly common sense.

- Make sure that the largest parts can be moved through the system without interference
- Design the system large enough for future volumes
- Pay close attention to features that can lead to cost savings, safety, or efficiency and be willing to spend extra money for them
- Consider operating cost as closely as capital cost
- Use durable building materials (stainless steel, heavy gauges, high efficiency fans, etc.)
- Consider maintenance issues and make sure all mechanical devices are easy to service

### 12.1.2 Quality

The level of quality that is required for the finished product has a direct influence on the cost of production. The desired level of quality will affect the pretreatment process, the application process, and the amount of rework or touch-up required.

Paint systems can be built to different standards of quality. The kind of system that will be required to produce top-quality appearance and performance will be quite different from one designed to apply paint to products that do not require very high standards for paint finish.

The definition of quality for an automobile exterior body finish is quite different from the quality standards for brake shoe. The car finish will require a very high standard for both appearance and performance, while the brake shoe needs some black paint that will last for a relatively short time and visual imperfections are not a big issue. The paint system for car bodies will be designed to provide a finish that is nearly perfect. No paint line will produce a 100% flawless finish, but there are many different standards for what is acceptable.

An absolutely flawless finish may be possible, but the cost will be very high. Some defects are likely on any paint line. Small defects in areas that are not right in the eye of the consumer may be acceptable. Larger defects in highly visible areas may be more objectionable. The question is, what level of defect is acceptable and what level of defect will cause a part to be rejected. A high-quality standard will require a better system, better controls, more inspection, and possibly more rework. It costs more to produce a better finish.

### 12.1.3 SUBSTRATE CONDITION

The condition of the part is also a major factor in the cost of the paint finish. Simple parts in high volume with very light soils will not cost nearly as much per square foot as complex shapes in low volume with heavy grease or other soils that need to be removed prior to paint application.

The substrate material, type of soil, volume of soil, and any other special considerations will impact the cost of part preparation. The part must be completely free of contamination before it can be painted. Castings have die release products, welded steel has burned-on oil, hot-rolled steel has mill scale, and aluminum has a tight oxide layer that can interfere with adhesion. The chemical in an alkaline cleaner may not be able to remove such contaminates. They may require additional process steps such as blasting or polishing. These additional steps will add to the cost.

### 12.1.4 RACKING

Another cost consideration is racking. Custom paint racks designed for a newly manufactured part can be very expensive. If the racks will improve the output volume and reduce costs, they may be worth the investment. To determine the value of purchasing custom-made tooling, the savings per piece and total run volume need to be compared to the cost of the tooling.

In many cases, there are existing hooks that can be used to hang the parts, but they are not always the most efficient way to maintain good line density and good throughput. For example, consider a situation where improved tooling would hold twice as many parts, and the cost for the tooling is $4000 (200 racks at $20 each). Existing utility racks are available that hold only two parts, while the new tooling will hold four parts in the same space on the conveyor.

#### 12.1.4.1 Line Data

Line speed—8 FPM
Rack spacing—2 ft centers
Hourly fixed cost—$400.00 (fixed cost includes administration, building cost, staff, etc.)

Fixed cost per piece with no racks purchased:

$$8\text{ FPM} \times 60\text{ min} = 480\text{ ft/h (FPH)}$$

$$\frac{480\text{ FPH}}{2'\text{ hanging centers}} = \frac{240\text{ racks}}{\text{h}}$$

$$240 \times 2\text{ parts/rack} = 480\text{ parts/h}$$

$$\frac{\$400.00\text{ (fixed cost/h)}}{480\text{ parts/h}} = \frac{\$0.83}{\text{part}}$$

Fixed cost per piece with special tooling:

$$240\text{ racks/h} \times 4\text{ parts/rack} = 960\text{ parts/h}$$

$$\frac{400}{960} = \frac{\$0.42}{\text{part}}$$

The savings per part is easy to calculate at \$0.41. The other piece of information that must be entered into the equation is the volume of parts to be run over time. For example, assume a volume of 2000 parts a month.

$$\$0.41\text{ savings/part} \times 2000\text{ parts/month} = \$820.00\text{ savings/month}$$

$$\frac{\$4000.00\text{ (new tooling cost)}}{\$820.00\text{ (savings/month)}} = 4.9\text{ months return on investment (ROI)}$$

The payback period for the special tooling in this example would be just under 5 months. In this example, the tooling would appear to be an excellent investment, but if the volume were a total of only 50 parts/month, it would probably not pay. Table 12.1 shows the payback with different volumes of production.

Of course, it is also possible to buy fewer racks, but they will cost more per rack. At any rate, it is important to evaluate the cost savings available from using custom-made tooling versus simple hooks that are used for utility purposes.

**TABLE 12.1**
**ROI for Different Volumes**

| Volume of Parts/Month | ROI |
|---|---|
| 500 | 19 months |
| 1000 | 9.5 months |
| 2000 | 4.75 months |
| 3000 | 3.17 months |

### 12.1.5 REWORK

Rework and scrap must be accounted for in determining the cost of a paint operation. Applying a second coat to the part is expensive. A second coat will add thickness that may not be acceptable. Some parts may need to be stripped, and in some cases, the part cannot be salvaged at all. The percentage of defects and the method for correcting them is an important cost issue. Every effort should be made to limit rework. Parts that are reworked need to be factored into any cost per part determination.

### 12.1.6 COLOR CHANGE

Color change time for liquid spray systems is very short, but has some impact on cost. Color change requires time and wastes material. Gaps in the line, cleaning solvents, and wasted paint are part of the total cost to paint the parts.

This is particularly true if the material being sprayed is a plural component material. Catalyzed materials are mixed in batches or mixed automatically by a computerized mixing device. Either way, some material must be purged from the lines for color change. The volume of catalyzed material that is purged to waste should be added to the piece price along with lost time for color change.

Of course, it must be recognized that we have a market economy, and the trend is to offer more color options, and current manufacturing trends are designed for just in time production and minimum inventories, limiting the control of the number of color changes in a typical line. The equipment should be designed to color-change as fast as possible with a minimum amount of wasted paint and solvent use.

## 12.2 APPLIED COST OF PAINT

The applied cost per square foot of a paint material can be calculated to determine the actual cost of painting the part. Special considerations like masking, film thickness requirements, and special part preparation should be factored into the total cost.

The cost of coating application is related to the material and efficiency of the paint application process. The following formulas provide a method of developing estimated coating cost per square foot. Actual costs of any process depend on the variables of the material price per unit, percentage solids, transfer efficiency, material utilization labor, and so forth.

### 12.2.1 COST PER SQUARE FOOT OF LIQUID SPRAY COATING

The number 1604 is used as a starting point (the coverage in square feet of 1 gal of paint that is 100% solids, at a film thickness of 1 mil and 100% efficiency). To determine the coverage of a gallon of paint, the first piece of information that is factored in is the percentage of solids. The solids content of the paint will provide the film, while the solvent and water content will evaporate.

$$\%\ \text{Solids} \times 1604 = \text{Theoretical coverage at } 100\%\ \text{efficiency } (\text{ft}^2/\text{gal, 1 mil thick})$$

**TABLE 12.2**
**Potential Transfer Efficiency of Spray Equipment**

| Spray Process | Transfer Efficiency (%) |
|---|---|
| Conventional air spray | 15–40 |
| Conventional airless | 20–50 |
| Conventional air-assisted airless | 30–60 |
| Conventional HVLP | 30–60 |
| Electrostatic airless | 40–70 |
| Electrostatic air spray | 40–80 |
| Electrostatic air-assisted airless | 50–85 |
| Electrostatic HVLP | 60–90 |
| Electrostatic bell atomization | 70–95 |
| Electrostatic disk atomization | 80–95 |
| Electrical atomization | 95–98 |

The actual film thickness and transfer efficiency is then added to the calculation.

$$\text{(Theoretical coverage/film thickness)} \times \text{Transfer efficiency}$$
$$= \text{Actual coverage, ft}^2\text{/gal}$$

After the actual coverage is determined, it is a simple step to calculate the applied cost.

$$\text{Cost/gal/actual coverage} = \text{Applied cost/ft}^2$$

Table 12.2 shows the theoretical transfer efficiency for different spray devices. Actual transfer efficiency can be calculated by determining how much paint it takes to cover a known square footage of part surface.

### 12.2.2 EXAMPLE OF COST CALCULATION

Assumed variables:

Cost/gal: \$21.00
% Solids: 60%
Film thickness: 1.2 mil
Application: electrostatic spray

$$0.60 \times 1604 = 962$$
$$962/1.2 \times 0.70 = 561$$
$$21/561 = \$0.0374/\text{ft}^2$$

In most cases, the cost of operation for the components of the system is part of a fixed operational cost per hour. The washer and ovens may use slightly more energy for a heavier part, but there is a cost to run them per hour no matter how much product is painted and shipped.

It is useful to know how much it costs to operate the equipment so that the total cost is known and so that equipment changes can be accurately evaluated. The cost to operate a paint system includes utilities (compressed air, gas, and electricity), water, chemicals, and maintenance. Some of these costs can be determined with standard formulas based on the size of the motors, burners, and fans.

### 12.2.3 COST OF SPRAY BOOTH EXHAUST

A spray booth exhausts air to dilute the concentration of solvents and contain oversprayed paint solids. The exhaust volume from the plant must be made up with outside air that must be heated when the outdoor temperature is cold. The amount of energy need depends on the location of the plant and the average outdoor temperatures.

The amount of spray booth exhaust, measured in cubic feet per minute (CFM), depends on the size of the booth opening and the required velocity of air to maintain a satisfactory atmosphere inside the booth. The design face-velocity depends on both the design and the application conditions. Occupational Safety and Health Administration (OSHA) requirements traditionally called for a minimum face velocity of 100 ft/min (FPM) in an occupied booth. Lower velocities are permissible in an automated booth, and the application system may also impact the design velocity. The opening area is multiplied times the design velocity to determine the exhaust volume.

$$\text{Spray booth opening (ft}^2\text{)} \times \text{Design face velocity (FPM)} = \text{Exhaust volume (CFM)}$$

The temperature difference is used to determine the amount of energy consumed in British thermal units per hour (Btu/h) and the cost of the fuel used to generate heat.

$$\text{Plant air temperature} - \text{Outside air temperature} = \text{Temperature rise}$$

The CFM is multiplied by the temperature rise and the value 1.1 to determine the Btu/h. The constant 1.1 is found by multiplying 0.018 (Btu/h required to raise 1 $\text{ft}^3$ of air 1°F at 100% efficiency) by 60 (converting CFM to cubic feet per hour, CFH). The value 1.08 is rounded to 1.1.

$$\text{CFM} \times \text{Temperature rise} \times 1.1 = \text{Btu/h at 100\% efficiency}$$

The Btu/h can be multiplied by the cost per 100 $\text{ft}^3$ of gas to determine the cost of the exhaust air; 100 $\text{ft}^3$ of gas is equal to 100,000 Btu/h.

$$\text{Btu/h}/100{,}000 \times \text{cost per 100 ft}^3 \text{ of gas} = \text{Spray booth exhaust \$/h.}$$

### 12.2.3.1 Example

Booth opening $\text{ft}^2$: 200
Design face velocity: 120 FPM
Outside air temperature: 50°F (from Table 12.3 of average degree days)
Plant air temperature: 70°F
Cost per 100 $\text{ft}^3$: \$0.45

$$200 \times 120 = 24{,}000 \text{ CFM}$$

$$70 - 50 = 20 \text{ temperature rise}$$

**TABLE 12.3**
**Average Temperature (Canadian Cities are in °C)**

| Location | Average[a] | Location | Average |
|---|---|---|---|
| Albany, NY | 48 | Memphis, TX | 62 |
| Albuquerque, NM | 55 | Miami, FL | 75 |
| Atlanta, GA | 62 | Milwaukee, WI | 48 |
| Baltimore, MD | 56 | Minneapolis, MN | 45 |
| Bismarck, ND | 41 | Mobile, AL | 68 |
| Boston, MA | 50 | Montreal, Que. | 7 |
| Buffalo, NY | 47 | Nashville, TN | 60 |
| Burlington, VT | 45 | New Orleans, LA | 70 |
| Calgary, Alta. | 4 | New York, NY | 52 |
| Cheyenne, WY | 45 | Oklahoma City, OK | 60 |
| Chicago, IL | 50 | Omaha, NE | 51 |
| Cleveland, OH | 49 | Philadelphia, PA | 54 |
| Columbia, SC | 64 | Phoenix, AZ | 70 |
| Concord, NH | 44 | Portland, ME | 46 |
| Dallas, TX | 66 | Providence, RI | 50 |
| Denver, CO | 50 | Quebec, Que. | 5 |
| Des Moines, IA | 50 | Rapid City, SD | 47 |
| Detroit, MI | 49 | Reno, NE | 50 |
| Great Falls, MT | 46 | Richmond, VA | 58 |
| Hartford, CT | 50 | St. Louis, MO | 50 |
| Honolulu, HI | 75 | Salt Lake City, MO | 51 |
| Houston, TX | 69 | San Francisco, CA | 56 |
| Indianapolis, IN | 53 | Seattle, WA | 52 |
| Jacksonville, FL | 69 | Toronto, Ont. | 8 |
| Juneau, AK | 42 | Vancouver, D.C. | 11 |
| Kansas City, MO | 55 | Washington, D.C. | 56 |
| Little Rock, AR | 62 | Wichita, KS | 57 |
| Los Angeles, CA | 63 | Winnipeg, Man. | 3 |
| Louisville, KY | 57 | | |

[a] *Source*: Weather Bureau/Department of Commerce.

$$24{,}000 \times 20 \times 1.1 = 528{,}000 \text{ Btu/h}$$

$$528{,}000/100{,}000 \times 0.45 = \$2.37/\text{h}$$

This formula for cost per Btu/h can be applied to washer burners or any other equipment.

### 12.2.4 SOLVENT-BASED LIQUID COATING OVEN EXHAUST REQUIREMENTS

An oven used for solvent-based paint must exhaust air to remove the volatile content from the solvents in the paint and the gases given off by the oven burner. The volume of exhaust, measured in CFM, and the temperature difference are the key variables.

$$\text{Gallons of paint/h} \times \% \text{ Solvent} = \text{Gallons of solvent/h}$$

The National Fire Protection Association (NFPA) recommends a minimum of 167 CFM of exhaust per gallon of solvent sprayed per hour.

$$\text{Gallons of solvent/h} \times 167 \text{ CFM/gallon} = \text{Exhaust CFM}$$

The CFM must be corrected for the temperature, as the air will expand when heated. The temperature correction uses the constant of 460, a number related to absolute zero, a hypothetical temperature characterized by the complete absence of heat and equivalent to approximately minus 460°F. The standard CFM (SCFM) are converted to actual CFM (ACFM) in the following equation:

$$\frac{\text{SCFM} \times (460 + \text{Maximum design temperature})}{460 + \text{Ambient Temperature}} = \text{ACFM}$$

The by-products of combustion must be added to the exhaust volume. The maximum burner Btu/h is divided by a recommended dilution rate to calculate the exhaust requirements. The recommended dilution rate to ensure that enough oxygen is present in the oven is 95 $\text{ft}^3/\text{s}$.

$$\text{Maximum burner Btu/h } (95 \text{ CFM} \times 60 \text{ s}) = \text{SCFM}$$

As in the ventilation requirement for the solvent concentration, the SCFM must be converted to ACFM with a temperature correction. The ventilation for solvents and burner gases are added together to determine the total CFM of exhaust. The exhaust can be converted to Btu/h, and the Btu/h can be used to determine cost as shown above with the spray booth calculation.

#### 12.2.4.1 Example

Oven set temperature: 375°F
Ambient air temperature: 70°F
Total exhaust: 1403 CFM
Cost per 100 $\text{ft}^3$: \$0.45

$$375 - 70 = 305$$

$$1403 \times 305 \times 1.1 = 470{,}707 \text{ Btu/h}$$

$$470{,}707/100{,}000 \times 0.45 = \$2.12/\text{h}$$

### 12.2.5 HEAT LOSS FROM LOADING

Another factor that adds to the cost of operating the oven is the amount of product and conveyor that travels through. Energy is expended to heat the product, racks, and chain.

$$\text{Oven set temperature} - \text{Ambient temperature} = \text{Oven temperature rise}$$

$$\text{Conveyor weight/ft} \times \text{FPM} \times 60 \text{ min}$$
$$= \text{Pounds of chain and trolley/h (see Table 12.4)}$$

(Use same formula for racks and parts)

$$\text{Conveyor chain and trolleys pounds/h} + \text{Racks pounds/h} + \text{Parts pounds/h}$$
$$= \text{Total loading}$$

$$\text{Oven temperature rise} \times \text{Total loading} \times \text{Specific heat load} = \text{Btu/h}$$

#### 12.2.5.1 Example

Oven set temperature: 375°F
Ambient air temperature: 70°F
Chain: 3″ I-Beam

**TABLE 12.4**
**Approximate Weight per Foot of Chain**

| Conveyor Type | Chain Weight/Foot | Trolley Weight |
|---|---|---|
| Enclosed track | 3.5 pounds | 0.5 pounds (H-attachment) |
| X348 | 2.14 pounds | 2.34 pounds |
| X458 | 3.14 pounds | 5.18 pounds |
| X678 | 6.39 pounds | 16.5 pounds |

**TABLE 12.5**
**Specific Heat Load of Some Common Materials**

| | | | | | |
|---|---|---|---|---|---|
| Metals | Steel—0.125 | Iron—0.130 | Aluminum—0.248 | Zinc—0.095 | Brass—0.092 |
| Plastics | ABS—0.3 | Nylon—0.4 | Phenolic—0.4 | Polystyrene—0.32 | Vinyl—0.2 |

**TABLE 12.6**
**Panel Loss Factor**

| Panel Thickness | Panel Loss Factor |
|---|---|
| 3″ | 0.40 |
| 4″ | 0.35 |
| 5″ | 0.30 |
| 6″ | 0.25 |
| 8″ | 0.20 |

Line speed: 10 FPM
Product loading: 6000 pounds (racks and parts, average)
Material: Steel

$$375 - 70 = 305$$

$$10 \text{ FPM} \times 4.5 \text{ lb/ft} \times 60 \text{ min} = 2700 \text{ lb chain/h}$$

$$2700 \text{ lb chain} + 6000 \text{ lb product} = 8700 \text{ lb/h}$$

$$305 \times 8700 \times 0.125 \text{ (from Table 12.5)} = 331{,}688 \text{ Btu/h}$$

### 12.2.6 RADIANT LOSSES

The last item that contributes to energy consumption in an oven is the radiant losses through the oven panels (see Table 12.6). The amount of loss depends on the oven temperature, the amount of insulation, and the oven size. The formula is shown below.

$$\text{Total oven surface area ft}^2 \times \text{Oven panel loss factor} \times \text{Oven temperature rise} = \text{Btu/h}$$

#### 12.2.6.1 Example

Oven size: 10′ $H$ × 25′ $W$ × 50 $L$
Panel thickness: 5″
Oven temperature rise: 305°F

Oven surface:

| | |
|---|---|
| Ends: 10 × 25 = 250 | 250 × 2 (ends) = 500 |
| Sides: 10 × 50 = 500 | 500 × 2 (sides) = 1000 |
| Top and bottom: 25 × 50 = 1250 | 1250 × 2 = 2500 |
| Total oven surface area, $ft^2$ | 4000 oven area |

$$4000 \times 0.30 \times 305 = 366{,}000\ \text{Btu/h}$$

### 12.2.7 LABOR AND MAINTENANCE COSTS

Obviously, the labor cost to run a system will vary with the size of the system, the level of quality expected, hours of production, frequency of color change, and many other variables. The following calculations are an outline of how to determine the cost to run a paint system. In order to accurately determine the cost of labor for coating a product the variables must be actual data from a particular line.

#### 12.2.7.1 Application Labor for Liquid Spray Coating

Labor costs w/fringes \$/h: Supervision—\$15.00
Paint mix—\$12.00
Applicators (2)—\$27.00
Total operator labor \$/h—\$54.00

Clean-up cost \$/h (man-hours/shift × \$/h)/operating h/shift

$$1\ \text{h} \times \$15 = 15 \qquad 15/8\ \text{h} = \$1.88$$

Maintenance labor cost (man-hours/wk × \$/h)/operating h/wk

$$8\ \text{h/wk} \times \$15 = 120 \qquad 120/40 = \$3.00$$

Spare parts cost (yearly parts cost/operating h/yr)

$$15{,}000/2{,}000 = \$7.50$$

Sludge disposal (lbs/h of coating × % transfer efficiency) × (% solids × disposal cost per gallon)

$$10.7\ \text{lb of coating} \times 0.30\ \text{TE} \times 0.60\ \text{solids} = 1.93 \qquad 1.93 \times 3.50 = \$6.76$$

Labor and maintenance cost \$/h

$$54 + 1.88 + 3.00 + 7.5 + 6.76 = \$73.14$$

#### 12.2.7.2 System Support Labor

The cost per year for support labor, such as rackers, hi-lo drivers, system maintenance, technicians, and so forth, will vary depending on the size of the system. A typical system might need one technician to oversee the mechanical and chemical maintenance of the system, one quality control manager, one hi-lo driver, and four rackers. At an average cost per hour of \$15.00/person, the support labor would cost \$105.00/h.

$$7 \text{ workers} \times 15.00/\text{h} = \$105.00/\text{h}.$$

Therefore, the total labor cost for the system might typically be \$178.05/h (73.05 + 105.00)

To determine the cost per piece, the hourly cost is divided into the total $\text{ft}^2$ painted per hour, then, the cost per $\text{ft}^2$ is multiplied times the $\text{ft}^2$ per piece.

#### 12.2.7.3 Example

Total $\text{ft}^2$/h: 6000
$\text{ft}^2$/piece: 0.5
Total application labor/h: 50.78
Total support labor/h: 105.00

$$50.78 + 105.00 = 155.78$$

$$\frac{155.78}{6000\ \text{ft}^2/\text{h}} = \frac{0.025}{\text{ft}^2}$$

$$0.025 \times 0.5 = \$0.0125/\text{piece}$$

### 12.2.8 ELECTRICAL CONSUMPTION

For single-phase motors, the full load amps (FLA) can be found on the motor chart (Table 12.7). To convert FLA to kilowatt-hours (kWh), the FLA is multiplied times the motor voltage to get watts and divided by 1000 to get kilowatts.

The formula for single-phase motors is:

$$\text{FLA} \times \text{volts} = \text{watts}$$

$$\frac{\text{Watts}}{1000} = \text{kilowatts}$$

The formula for three-phase is

$$\text{Volts} \times \text{amps} \times 1.73 \times \text{power factor} = \text{watts}$$

$$\frac{\text{Watts}}{1000} = \text{kilowatts}$$

$$\text{Kilowatts} \times \text{cost/kWh} = \text{hourly operating cost}$$

**TABLE 12.7**
**Motor FLA at 1800 rpm**

| HP | 230 V | 460 V | HP | 230 V | 460 V | HP | 230 V | 460 V |
|---|---|---|---|---|---|---|---|---|
| FLA of three-phase induction motors 60 cycles, 1800 rpm | | | | | | | | |
| 1/4 | 0.96 | 0.48 | 10 | 24.5 | 12.3 | 100 | 233 | 116 |
| 1/3 | 1.16 | 0.58 | 15 | 36.7 | 18.4 | 125 | 289 | 144 |
| 1/2 | 1.68 | 0.84 | 20 | 49.0 | 24.5 | 150 | 346 | 173 |
| 3/4 | 2.33 | 1.17 | 25 | 62.7 | 31.3 | 200 | 460 | 230 |
| 1 | 2.75 | 1.38 | 30 | 72.8 | 36.4 | 250 | 572 | 286 |
| 1.5 | 4.17 | 2.09 | 40 | 98.0 | 49.0 | 300 | 685 | 342 |
| 2 | 5.56 | 2.78 | 50 | 121 | 60.5 | | | |
| 3 | 7.87 | 3.94 | 60 | 143 | 71.5 | | | |
| 5 | 12.7 | 6.34 | 75 | 178 | 89.0 | | | |
| 7.5 | 19.2 | 9.60 | | | | | | |
| FLA of single-phase induction motor 60 cycles, 1800 rpm | | | | | | | | |
| 1/8 | 2.80 | 1.40 | 3/4 | 10.20 | 5.10 | 3 | 34.00 | 17.00 |
| 1/6 | 3.20 | 1.60 | 1 | 13.00 | 6.50 | 5 | 56.00 | 28.00 |
| 1/4 | 4.60 | 2.30 | 1 1/2 | 18.40 | 9.20 | 7 1/2 | 80.00 | 40.00 |
| 1/3 | 5.20 | 2.60 | 2 | 24.00 | 12.00 | 10 | 100.00 | 50.00 |
| 1/2 | 7.40 | 3.70 | | | | | | |

The power factor will vary with different motors between 0.7 and 0.9. Using 0.75 as a typical number will give relatively close accuracy.

### 12.2.8.1 Example

10-hp motor, 460/3/60

$$460 \times 12.6 \times 1.73 \times 0.75 = 7520$$

$$\frac{7520}{1000} = 7.5 \text{ kWh}$$

These costs are based on the motor running at full load, which they rarely do in production. Actual numbers can be determined by taking an amp draw from the motor and following the formula, substituting the actual amps for the FLA listed on the chart. The current draw at start-up will be higher than the current draw during operation. Some larger motors will need a power correction factor of 1.1 or 1.25.

## 12.2.9 COMPRESSED AIR

Compressed air is used to operate the spray equipment, pumps, and valves and it may also have several other uses within the operation of a paint system. Compressed air is measured by volume in SCFM and by pressure in pounds per square inch (psi).

One SCFM of compressed air requires approximately 0.21 kWh to generate. At a cost of approximately \$0.08/kWh, the cost of one SCFM of compressed air is around \$0.017/h.

$$0.21 \text{ kWh} \times 0.08/\text{kWh} = 0.017/\text{h}.$$

Spray equipment manufacturers can supply the maximum compressed air consumption for their equipment. Some typical maximum consumption volumes are shown next for various components in a sample paint system.

Spray gun: 8 CFM
Agitator: 3 CFM
Pump: 7 CFM
Other: 5 CFM

A typical automated system for liquid application might have several stations for application, some automatic and some manual. A typical system might have as many as 10–14 guns or more. Compressed air consumption will average around 100 CFM. The air compressor sizing should consider the maximum consumption at any one time, not the average consumption (see Table 12.8).

Air leaks in the system should be avoided. Table 12.9 shows the losses associated with air leaks.

Air leaks can occur from worn valves, bad seals, poor connections (hose to fitting), and leaky disconnects. It is wise to inspect the lines periodically to see if all of the connections are leak free.

### TABLE 12.8
### Air Compressor Sizing Based on Horse Power

| Compressor HP | 3 | 5 | 7.5 | 10 | 15 | 20 | 25 | 30 | 50 |
|---|---|---|---|---|---|---|---|---|---|
| Maximum CFM at 100 psi | 12 | 20 | 30 | 40 | 60 | 80 | 100 | 120 | 200 |

### TABLE 12.9
### Cost of Air Leaks

| Hole Size of Loss | $ft^3$ Waste at 100 psig and 720 h/Month | Cost/Month at \$0.20/1000 $ft^3$ |
|---|---|---|
| 1/2″ | 17,928,000 | \$3,585.60 |
| 3/8″ | 10,108,800 | \$2,021.76 |
| 1/4″ | 4,492,800 | \$898.56 |
| 1/8″ | 1,123,200 | \$224.64 |
| 1/16″ | 280,370 | \$56.07 |

### 12.2.10 TOTAL COST OF PAINT APPLICATION

The total cost of application can be calculated using a standard accounting formula. The costs can be included in whatever heading a company chooses as long as each cost item is captured.

Historical data are always best, but the costs can also be estimated based on standard formulas. The following outline shows a step-by-step quote for the cost of paint application.

### 12.2.11 QUOTING A PART

When quoting the cost of application of a particular paint to a particular part the first step is to create a list of production information that defines how the part will be run. The annual volume to be painted will be important when making decisions about investment in tooling or other items that can improve efficiency. The set-up volume (number of parts per run) is also important as it will affect the amount of tooling and influence set-up costs, color change, and other adjustments that will be necessary for that part.

The square footage of the part must be measured to determine the surface area that will be painted. Parts with complex geometry can be broken down into measurable geometric shapes as shown in Appendix B.

Process data are used to determine the parts per hour so that the hourly costs can be broken down into a cost per part.

- Design racking configuration (total parts per rack or hook)
- Rack or hook spacing on the conveyor (rack center distance in feet)
- Conveyor line speed (FPM)
- Downtime factor (15–20% typical)

This information is used to calculate the cost of each item that influences the ultimate cost to paint the part, including the material cost, labor, burden, fixed cost, and scrap cost. The first step is to determine a production rate.

$$\text{Conveyor speed (FPM)} \times 60\ \text{min} = \text{FPH}$$

$$\frac{\text{Parts/rack}}{\text{Rack spacing}} = \text{Parts/foot}$$

$$\text{FPH} \times \text{Parts/foot} = \text{Parts/h at 100\% uptime}$$

Add downtime factor:

$$\text{Parts/h at 100\% uptime} \times 0.80 = \text{Parts/h at 80\% uptime}$$

#### 12.2.11.1 Material Cost

The material cost follows the formulas supplied for liquid coatings.

$$\% \text{ Solids} \times 1604 = \text{Theoretical coverage at } 100\% \text{ Efficiency } (\text{ft}^2/\text{gal, 1 mil thick})$$

$$(\text{Theoretical coverage/film thickness}) \times \text{Transfer efficiency} = \text{Actual coverage, ft}^2/\text{gal}$$

- Adjust the $\text{ft}^2$ for paint losses on the rack; assume a percentage of the part $\text{ft}^2$
- For large parts the percentage will be lower, because there will be more part and less rack
- For smaller parts, the percentage will be higher
- For film thickness use a default of 1 mil

$$\frac{\text{Cost of paint}}{\text{ft}^2/\text{gallon}} = \text{cost/ft}^2$$

$$\text{Cost/ft}^2 \times \text{ft}^2/\text{part} = \text{material cost/part}$$

Add start up waste (purging and charging the system) to the cost of material.

$$\text{Cost/gal} \times \text{waste} = \text{total start up material cost}$$

$$\frac{\text{Start up material cost}}{\text{parts per typical run}} = \text{cost per part of waste addition}$$

$$\text{Material cost per part} + \text{Waste material per part} = \text{Total material cost/part}$$

#### 12.2.11.2 Labor

To determine the cost of labor the number of people and the costs for their labor is totaled and compared to the output per hour.

Line personnel include sprayers, quality control people, supervisors, rackers (online and off-line) and others (masking, blow-off, etc.).

The average straight wage is used to determine the total cost of labor per hour, and then the total labor cost is divided by the production volume to determine the cost per part.

$$\text{Average wage/h} \times \text{Number of people} = \text{Total straight wage}$$

$$\frac{\text{Total straight wage}}{\text{Parts/h}} = \$/\text{part}$$

#### 12.2.11.3 Burden

Burden is a cost that is added to labor and line operation for additions to hourly wage (insurance, uniforms, training, taxes, etc.) and special materials used to run a particular part (utilities, packaging, supplies, testing, etc.).

Variable labor can often be expressed as a percentage of straight wages, say 25%.

$$\text{Total direct labor} \times \text{Addition }\% = \text{Variable labor addition}$$

Variable line burden can be calculated by collection of data for items that fit into this category. The cost of the items that support the line is broken down into an hourly cost, added to the hourly cost of variable labor, and then divided by the production rate to determine the cost per part.

$$\frac{\text{Hourly cost of burden}}{\text{Parts/h}} = \text{Cost/part}$$

#### 12.2.11.4 Fixed Cost

Fixed cost is the cost of operating a business that is steady and ongoing, regardless of the number of parts that are painted. This includes building cost, debt, administration, and maintenance. Data for these costs is collected and divided into an hourly fixed cost. The hourly fixed cost is divided into the production rate to determine the cost per part.

$$\frac{\text{Total fixed cost/h}}{\text{Parts/h}} = \text{Cost/part}$$

#### 12.2.11.5 Scrap Cost

Scrap and rework should be added to the cost per part. The cost of parts that have to be repainted and the number that have to be thrown away should be totaled and divided into the production volume and added to the total cost per part.

#### 12.2.11.6 Add Cost

The total cost of painting the part is the sum of the all the items listed above.

- Material cost
- Labor cost
- Burden
- Fixed cost
- Scrap cost

The final price may be adjusted for special considerations. Things like masking and special packaging should be factored into the cost. Low volumes may make the price higher just as high volumes may reduce the cost.

Any cost that requires payment by the company should be reflected in the per piece cost. It may not be immediately clear what category the item should be placed in and some items may fit into more than one category. It does not matter what category a cost item is put into as long as it is included and the method is consistent.

# APPENDIX A

## METRIC EQUIVALENTS

### Degrees Fahrenheit to Degrees Celsius

| °F | °C | °F | °C | °F | °C |
|---|---|---|---|---|---|
| 0 | −17.8 | 110 | 43.3 | 310 | 154.4 |
| 5 | −15.0 | 120 | 48.9 | 320 | 160.0 |
| 10 | −12.2 | 130 | 54.4 | 330 | 165.6 |
| 15 | −9.4 | 140 | 60.0 | 340 | 171.1 |
| 20 | −6.7 | 150 | 65.6 | 350 | 176.7 |
| 25 | −3.9 | 160 | 71.1 | 360 | 182.2 |
| 30 | −1.1 | 170 | 76.7 | 370 | 187.8 |
| 35 | 1.7 | 180 | 82.2 | 380 | 193.3 |
| 40 | 4.4 | 190 | 87.8 | 390 | 198.9 |
| 45 | 7.2 | 200 | 93.3 | 400 | 204.4 |
| 50 | 10.0 | 210 | 98.9 | 410 | 210.0 |
| 55 | 12.8 | 220 | 104.4 | 420 | 215.6 |
| 60 | 15.6 | 230 | 110.0 | 430 | 221.1 |
| 65 | 18.3 | 240 | 115.6 | 440 | 226.7 |
| 70 | 21.1 | 250 | 121.1 | 450 | 232.2 |
| 78 | 23.9 | 260 | 126.7 | 460 | 237.8 |
| 80 | 26.7 | 270 | 132.2 | 470 | 243.3 |
| 85 | 29.4 | 280 | 137.8 | 480 | 248.9 |
| 90 | 32.2 | 290 | 143.3 | 490 | 254.4 |
| 95 | 35.0 | 300 | 148.9 | 500 | 260.0 |
| 100 | 37.8 | | | | |

### Conversion Tables

| If you Know | Multiply by | To Find |
|---|---|---|
| Inches | 2.540 | Centimeters |
| Inches | 25.40 | Millimeters |
| Inches | 1000.0 | Mils |
| Feet | 30.48 | Centimeters |
| Meters | 100.0 | Centimeters |
| Meters | 39.37 | Inches |
| Meters | 3.281 | Feet |
| Kilogram-calories | 3.968 | Btu |
| Kilowatt-hours | 3,413.0 | Btu |
| Liters | 0.2642 | Gallons (U.S. liquid) |
| Feet/min | 0.3048 | Meters/min |
| Square feet | 929.0 | Square centimeters |
| Square meters | 10.76 | Square feet |
| Mils | 0.001 | Inches |
| Poise | 1.00 | Gram/cm s |

# APPENDIX B

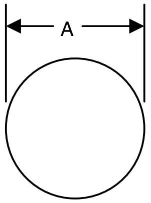
## COMMON GEOMETRIES AND FORMULAS FOR CALCULATION OF AREA

### *CIRCLE*

$$\text{Area} = 0.785 \times \text{Square of the diameter} = 0.785 \times (A)^2 = 0.785 \times A \times A$$

Example—
The circle is 4″ in diameter

$$\text{Area} = 0.785 \times (4)^2 = 0.785 \times 4 \times 4 = 12.56 \text{ in.}^2$$

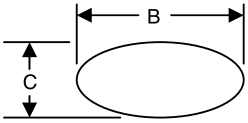


### *ELLIPSE*

$$\text{Area} = 0.785 \times \text{Long diameter} \times \text{Short diameter} = 0.785 \times B \times C$$

Example—
Ellipse 4″ × 3″

$$\text{Area} = 0.785 \times 4 \times 3 = 9.42 \text{ in.}^2$$

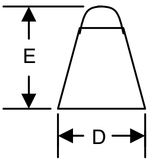


### *PARABOLA*

$$\text{Area} = 2/3 \text{ Base} \times \text{Height} = 2/3 \times D \times E$$

Example—
Base is 3″ and the height is 5″

$$\text{Area} = 2/3 \times 3 \times 5 = 10 \text{ in.}^2$$

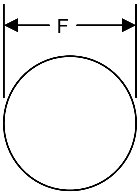


### *SPHERE*

$$\text{Area} = 3.14 \times \text{Square of diameter—}3.14 \times (F)^2 = 3.14 \times F \times F$$

Example—
Sphere is 5″ in diameter

$$\text{Area} = 3.14 \times (5)^2 = 3.14 \times 5 \times 5 = 78.5\ \text{in.}^2$$



### *CYLINDER*

1. Hollow

$$\text{Area} = \text{Circumference} \times \text{Length} = 3.14 \times H \times G$$

Example—
Tube 4″ in diameter and 12″ long

$$\text{Area} = 3.14 \times 4 \times 12 = 150.7\ \text{in.}^2$$

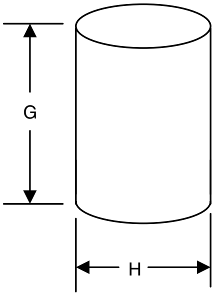
2. Solid

$$\text{Area} = \text{Circumference} \times \text{Length plus twice cross} - \text{sectional area}$$

$$3.14 \times H \times G + 1.57 \times H \times H = \text{Area to be covered}$$

Example—
Round bar is 4″ in diameter and 12″ long

$$\begin{aligned} \text{Area} = 3.14 \times 4 \times 12 &= 150.7 \\ +1.57 \times 4 \times 4 &= 25.1 \\ &= 175.8\ \text{in.}^2 \end{aligned}$$



*CONE*

1. Hollow

$$\text{Area} = 1/2 \text{ of circumference of base} \times \text{slant height} 1.57 \times \text{K} \times \text{J}$$

Example—
Cone is 4″ in diameter at base and 6″ slant height

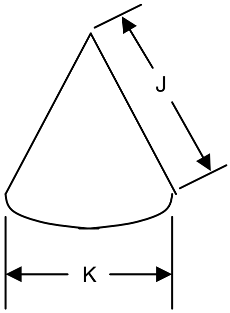
$$\text{Area} = 1.57 \times 4 \times 6 = 37.68 \text{ in.}^2$$

2. Solid

$$\text{Area} = 1.57 \times \text{K} \times \text{J} + 0.785 \times \text{K} \times \text{K}$$

Example—
Same as above

$$\text{Area} = 1.57 \times 4 \times 6 + 0.785 \times 4 \times 4 = 37.68 + 12.56 = 50.24 \text{ in.}^2$$



*FRUSTRUM OF CONE*

1. Hollow

$$\begin{aligned}\text{Area} &= 1/2 \text{ sum of circumference of bases} \times \text{slant height}\\ &= 1.57 \times (\text{M} + \text{N}) \times \text{L}\end{aligned}$$

Example—
A tapered tube 4″ diameter at small end, 6″ diameter at large end, and 6″ slant height

$$\text{Area} = 1.57 \times (6 + 4) \times 6 = 94.2 \text{ in.}^2$$

2. Solid

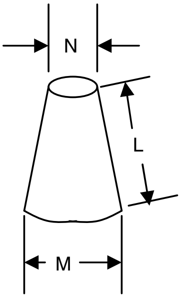
$$\begin{aligned}\text{Area} = 1/2 \text{ sum of circumference of bases} + \text{slant height}\\ + \text{sum of areas of bases}\end{aligned}$$

$$1.57 \times (\text{M} + \text{N}) \times \text{L} + 0.785 \times (\text{M}^2 + \text{N}^2) = \text{in.}^2$$

Example—
A tapered bar 4″ diameter at small end, 6″ diameter at large end and 6″ slant height

$$\text{Area} = 1.57 \times (6 + 4) \times 6 + 0.785 \times (6 \times 6 + 4 \times 4) = 94.2 + 40.8$$
$$= 135 \text{ sq. in.}$$

On all cylinders, cones, and frustums of cones that are hollow and where it is desired to know the area that must be covered, if outside and inside areas are to be determined, the average of the outside and inside diameters should be used in the formulas and the result doubled.

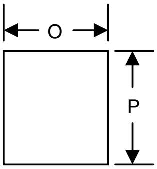


*SQUARE*

$$\text{Area} = O \times P$$

Example—
Square 5″ on a side

$$\text{Area} = 5 \times 5 = 25 \text{ in.}^2$$

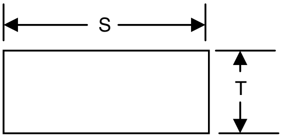


*RECTANGLE*

$$\text{Area} = S \times T$$

Example—
Rectangle 5″ × 3″

$$\text{Area} = 5 \times 3 = 15 \text{ in.}^2$$



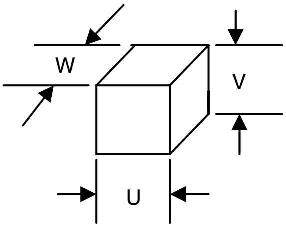
### *CUBE*

(All sides equal)

$$\text{Area} = 6 \times \text{square of one side}$$

Example—
Cube 6″ on one side

$$\text{Area} = 6 \times (6)^2 = 216\ \text{in.}^2$$



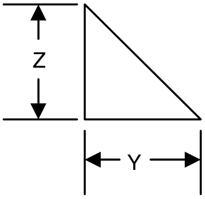
### *TRIANGLE*

$$1/2 \times \text{base} \times \text{altitude}$$

$$\text{Area} = 1/2 \times Y \times Z$$

Example—
Base of triangle is 8″ and height is 6″

$$\text{Area} = 1/2 \times 8 \times 6 = 24\ \text{in.}^2$$



### *HEXAGON*

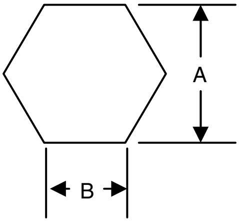
(Six equal sides—all angles equal)

$$\text{Area} = 3/2 \times \text{length of one side} \times \text{distance between any two parallel sides}$$

$$\text{Area} = 3/2 \times B \times A$$

Example—
Hexagon 2″ on a side and 4″ between flats

$$\text{Area} = 3/2 \times 2 \times 4 = 12 \text{ in.}^2$$

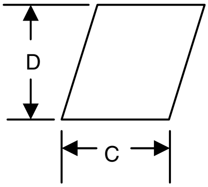


*PARALLELOGRAM*
(Opposite sides parallel)

$$\text{Area} = \text{Length of side} \times \text{Vertical distance to parallel side} = C \times D$$

Example—
A parallelogram with one side of 6″ and a distance of 4″ between this side and the parallel side.

$$\text{Area} = 6 \times 4 = 24 \text{ in.}^2$$

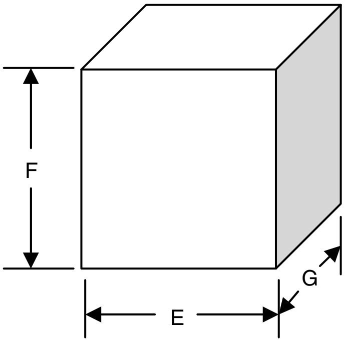


*RECTANGULAR PARALLELOPIPED*
(Opposite sides parallel)

$$\text{Area} = 2 \times (E \times F + F \times G + G \times E) = \text{Surface}$$

Example—
A block having sides 4″, 6″, and 8″ long, respectively

$$\text{Area} = 2 \times (4 \times 6 + 6 \times 8 + 8 \times 4) = 208\ \text{in.}^2$$

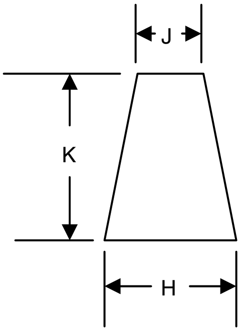


*TRAPEZOID*
(One pair of opposite sides parallel)

$$\begin{aligned}\text{Area} &= 1/2 \text{ sum of the parallel sides} \times \text{vertical distance between them}\\ &= 1/2 \times (H + J) \times K\end{aligned}$$

Example—
A trapezoid having parallel sides 6″ and 4″ long respectively, distance between them being 4″

$$\text{Area} = 1/2 \times (6 + 4) \times 4 = 20\ \text{in.}^2$$



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**Materials Science**

From cars to furniture, computers, and mechanical components, paints and coatings play a vital role in nearly every manufactured product available. Written by an industry insider with more than 30 years of experience, the **Paint Technology Handbook** provides a practical and straightforward guide for the design of coatings systems. The author emphasizes the importance of understanding paint materials, manufacturing techniques, testing, application methods, and equipment in order to meet product-specific needs.

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